Physics At Future Colliders

Brookhaven Forum 2015: Great Expectations, a New Chapter

Oct. 9, 2015

Tao Han

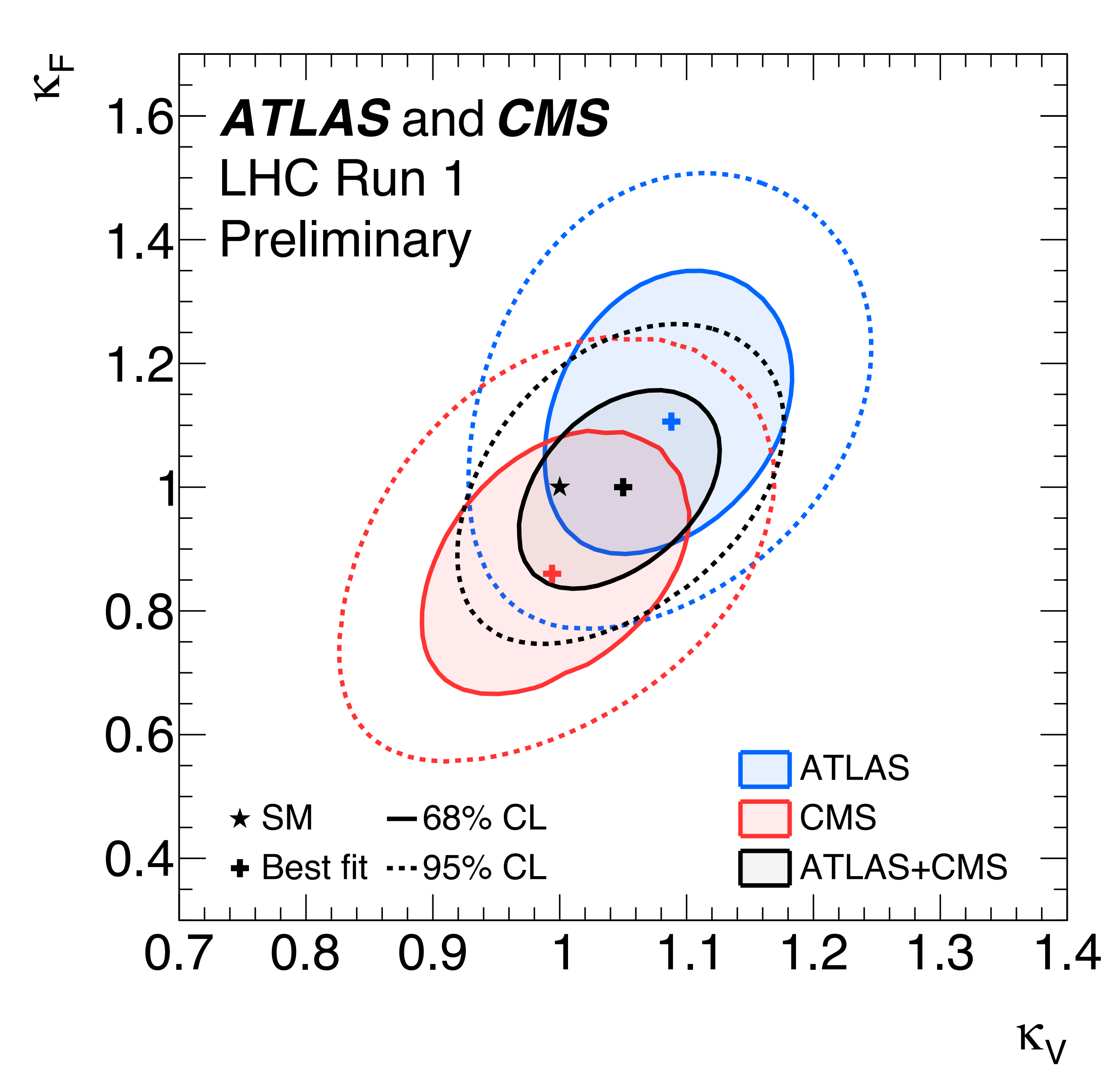
TLEP Report 1308.6176; CEPS pre-CDR; Snowmass Reports
N. Arkani-Hamed, T. Han, M. Mangano, L.T. Wang, in prep

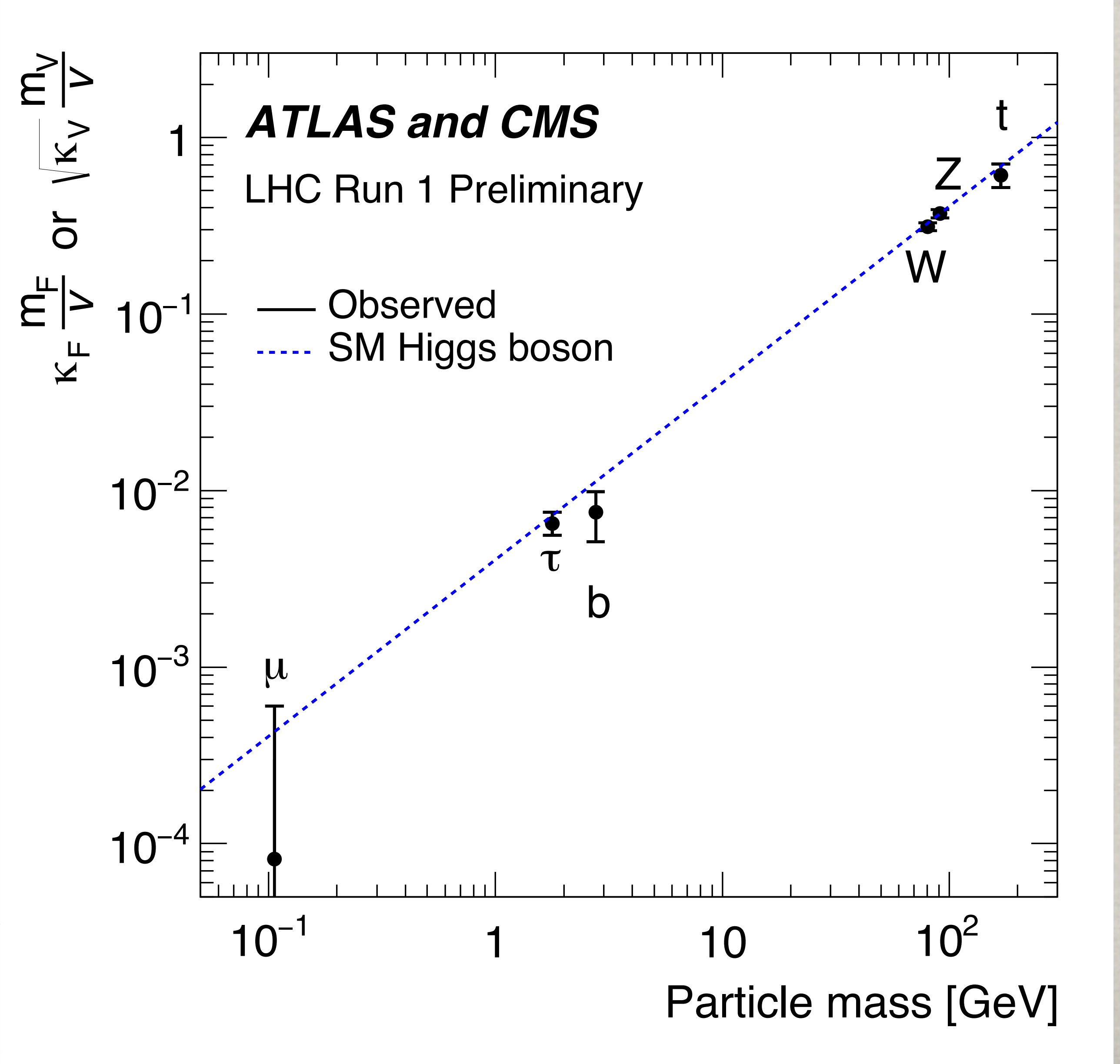
High Energy Physics IS at an extremely interesting time:

The milestone discovery:

5σ for both $h \rightarrow \tau\tau$; $WW \rightarrow h$

Very SM-like

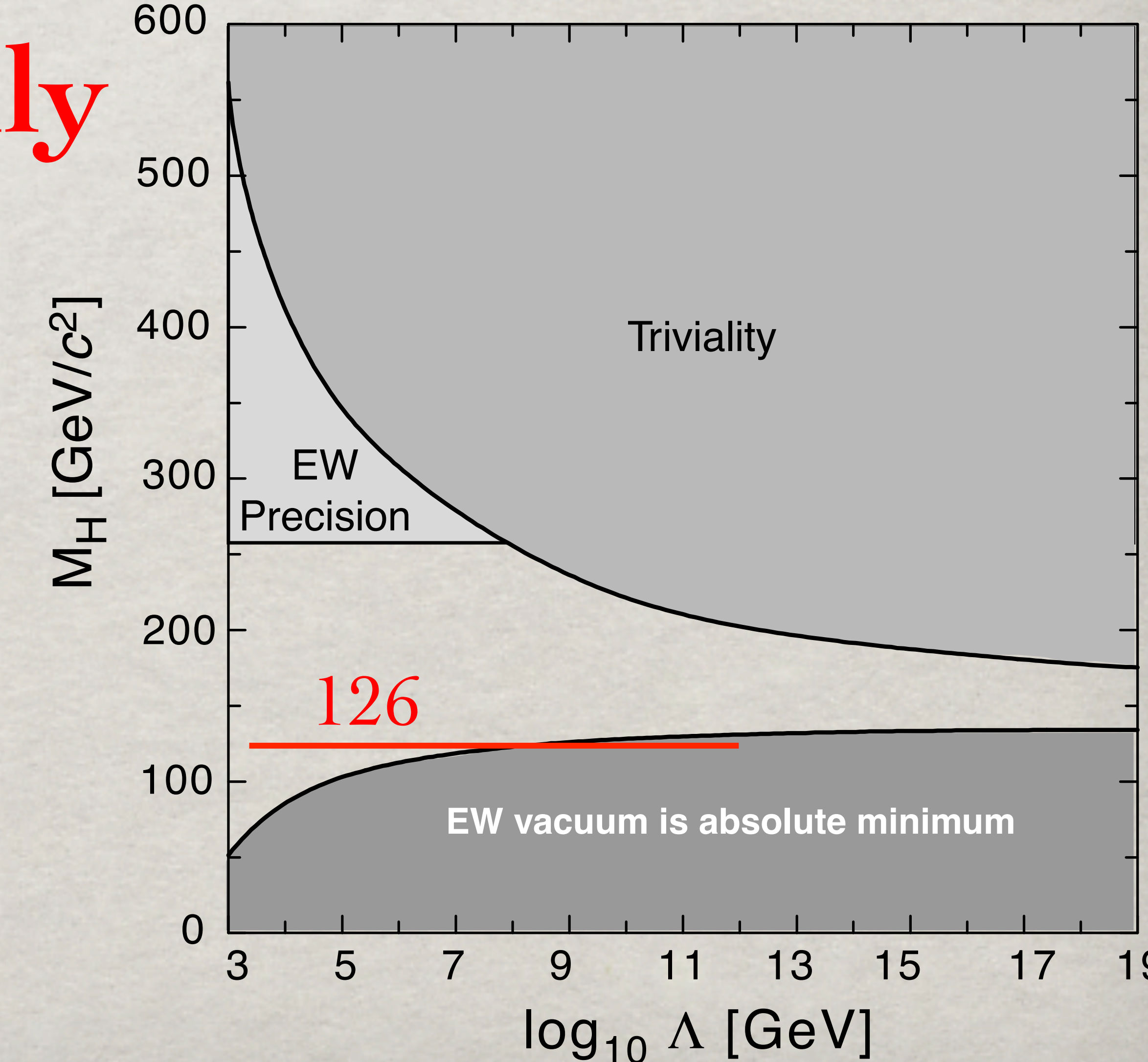




The completion of the SM:

First time ever, we have a consistent relativistic/quantum mechanical theory: weakly coupled, unitary, renormalizable, vacuum (quasi?)stable

valid up to an exponentially high scale, perhaps to the Planck scale M_{Pl}!



“… most of the grand underlying principles have been firmly established. An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals. ”

--- Albert Michelson (1894)

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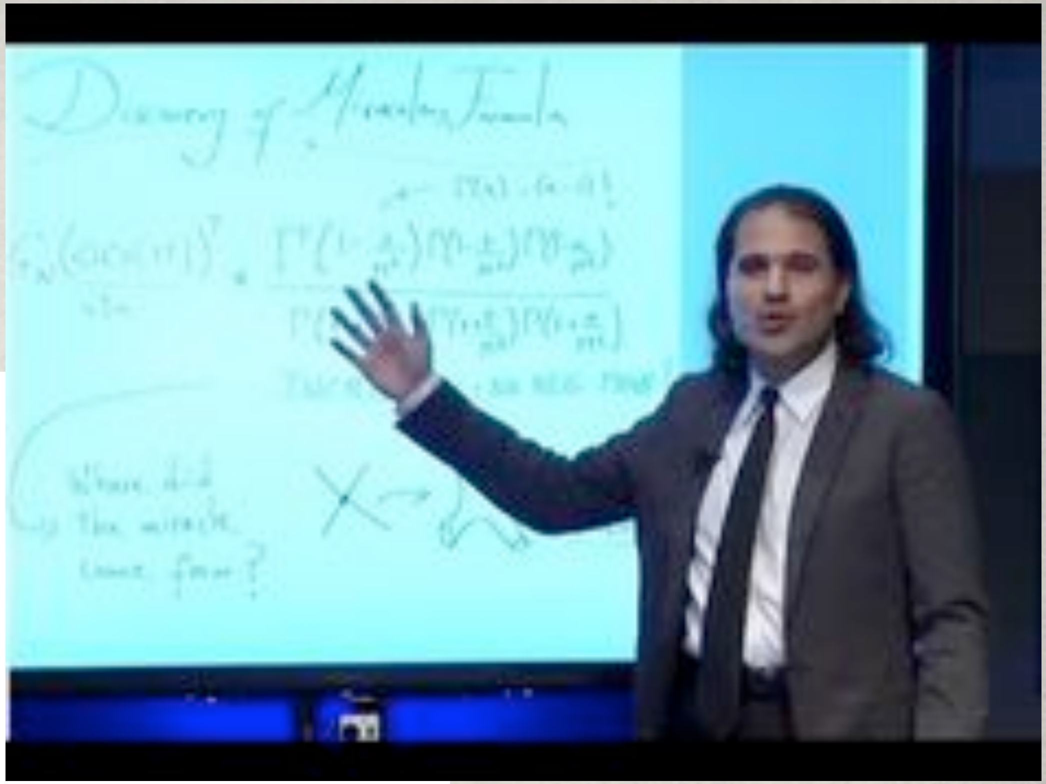
Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

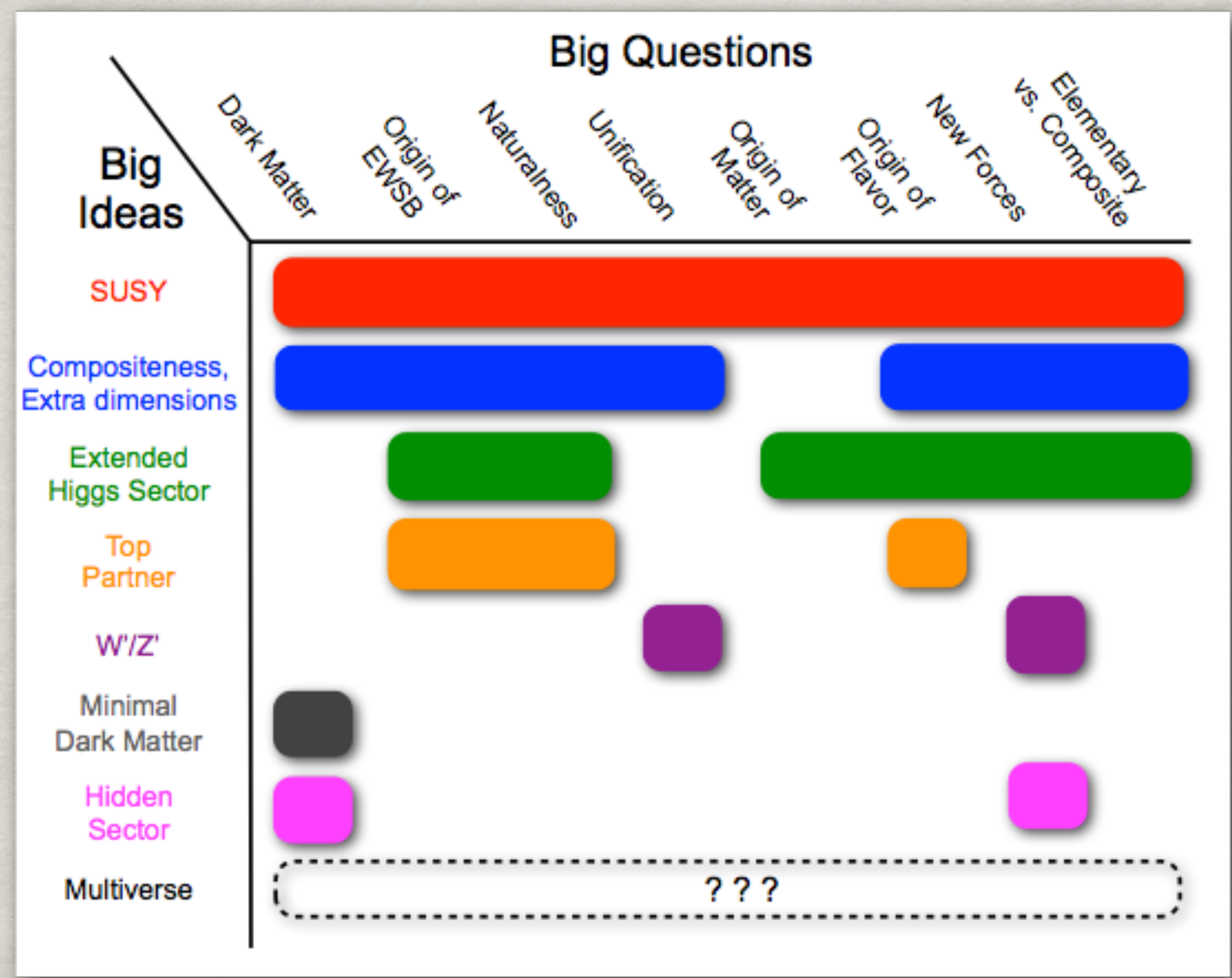
Will History repeat itself (soon)?

Nima Arkani-Hamed
(Director of CFHEP, Beijing)



The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model $\to$ real theory

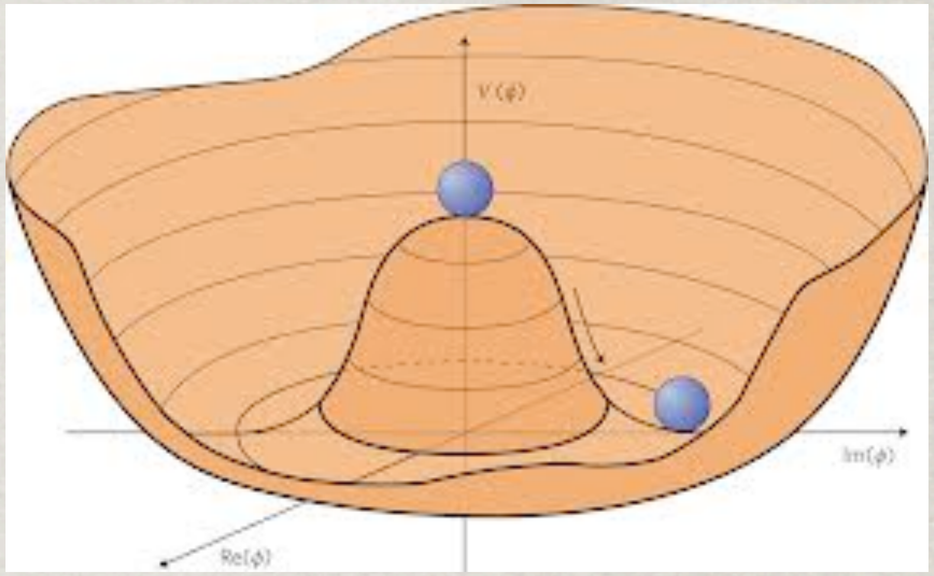
Snowmass NP report, 1311.0299



New Era:
Under the Higgs lamp post

Question 1: The Nature of EWSB ?

In the SM:



$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$\Rightarrow \quad \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

Fully determined at the weak scale:

$v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV $\quad m_H \approx 126$ GeV

$$m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89 \text{ GeV}, \quad \lambda \approx \frac{1}{8}.$$

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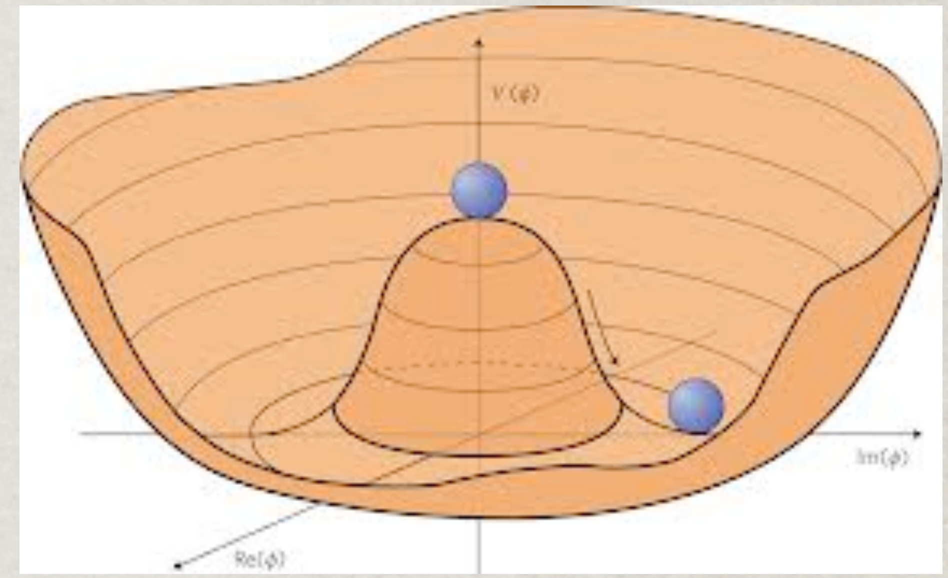

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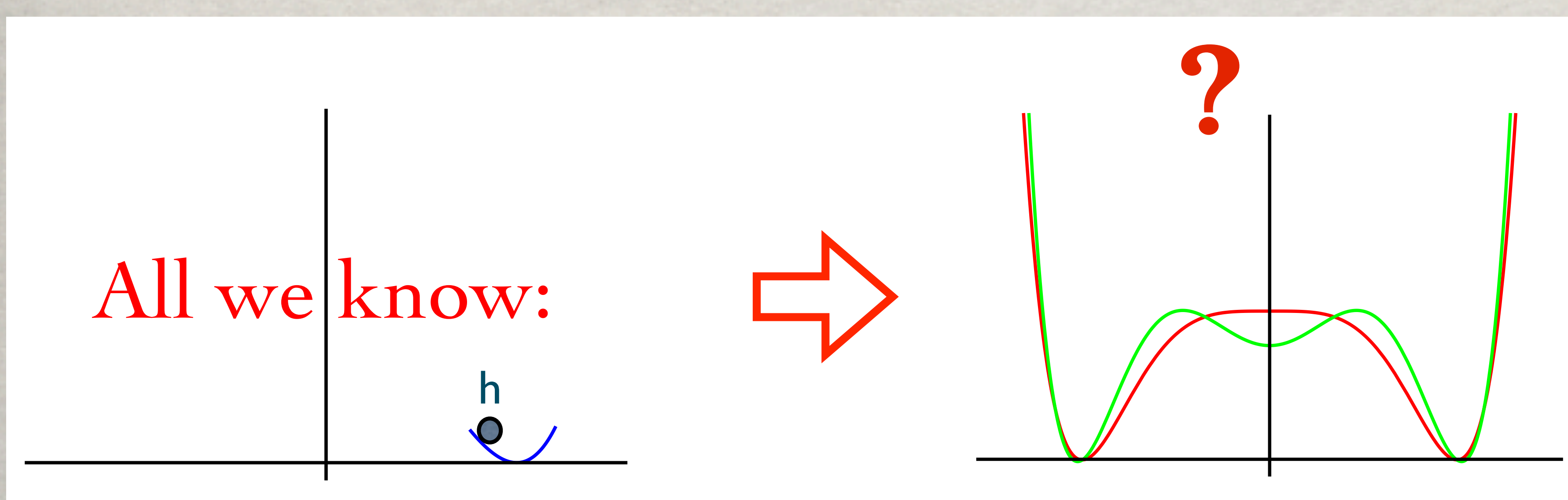
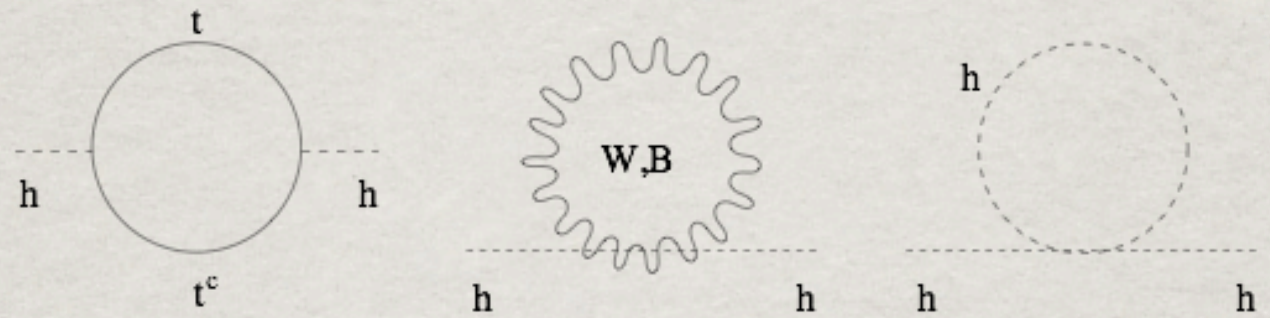


O(1) deviation on λ_{hhh} could make EW phase transition strong 1st order!

X.M.Zhang (1993); C. Grojean et al. (2005)

Question 2: The "Naturalness"

Higgs mass is "un-natural" in the Wilson/ 't Hooft sense:



(a) (b) (c)

$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

Cancelation in perspective:

$m_H{}^2$ = 36,127,890,984,789,307,394,520,932,878,928,933,023

–36,127,890,984,789,307,394,520,932,878,928,917,398

= $(125\ \mathrm{GeV})^2$! ?

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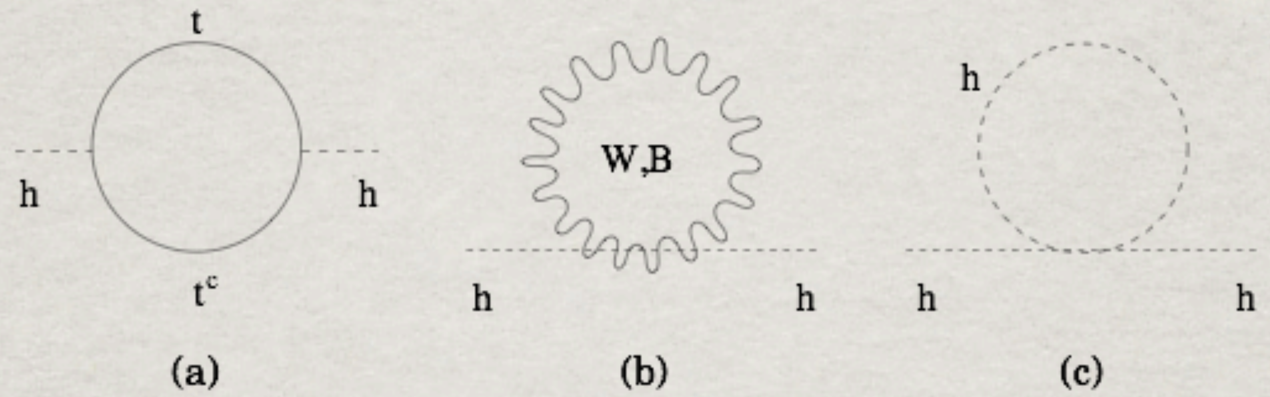

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= $(125 \text{ GeV})^2$! ?

Natural: O(1 TeV) new physics, associated with ttH.

Unknown: Deep UV-IR correlations?

Agnostic: Multiverse/anthropic?

Question 3: The Dark Sector

The un-protected operator may reveal secret

Higgs portal: $k_s H^\dagger H \ S^* S, \quad \dfrac{k_\chi}{\Lambda} H^\dagger H \ \bar{\chi}\chi.$

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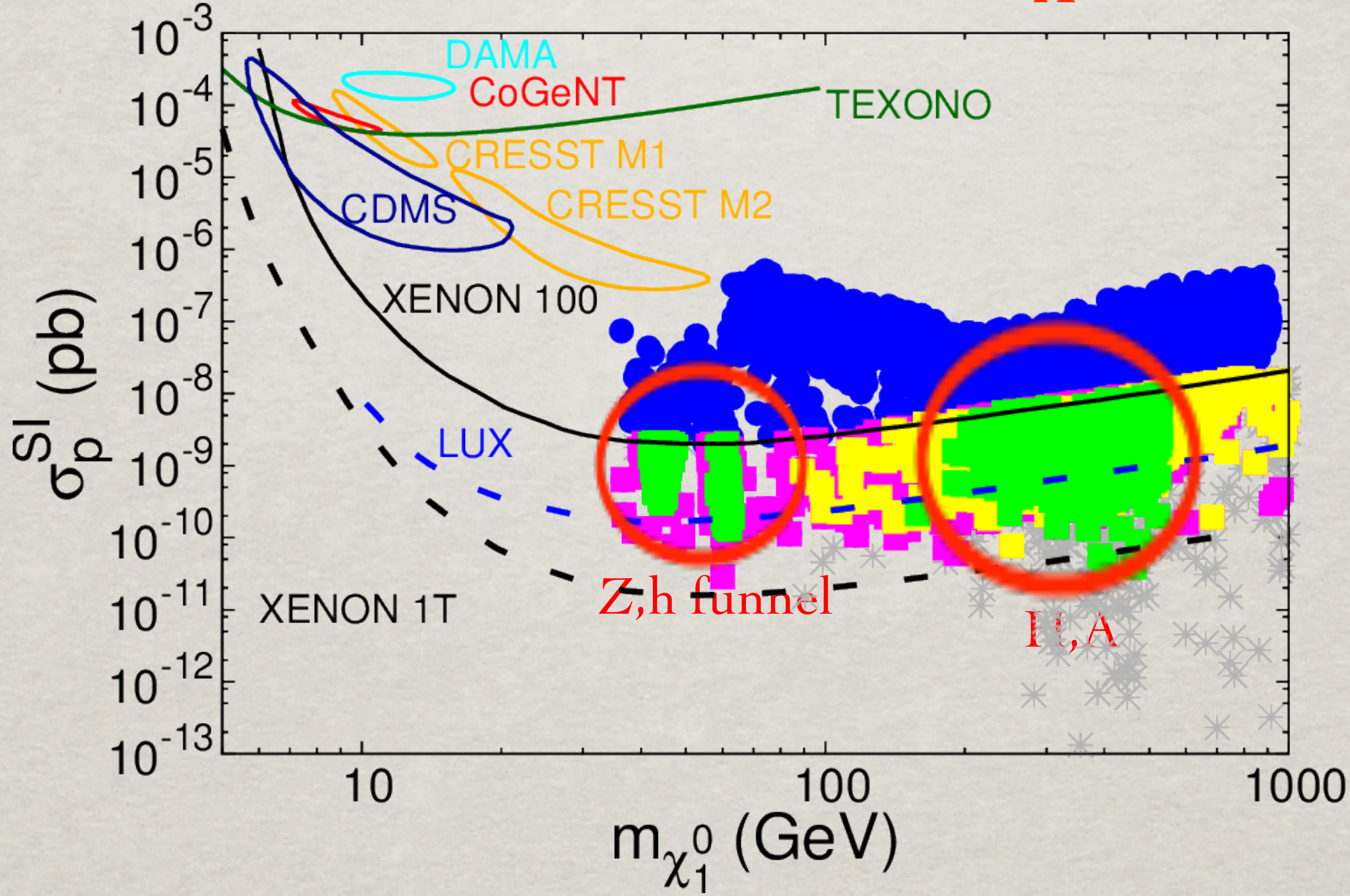
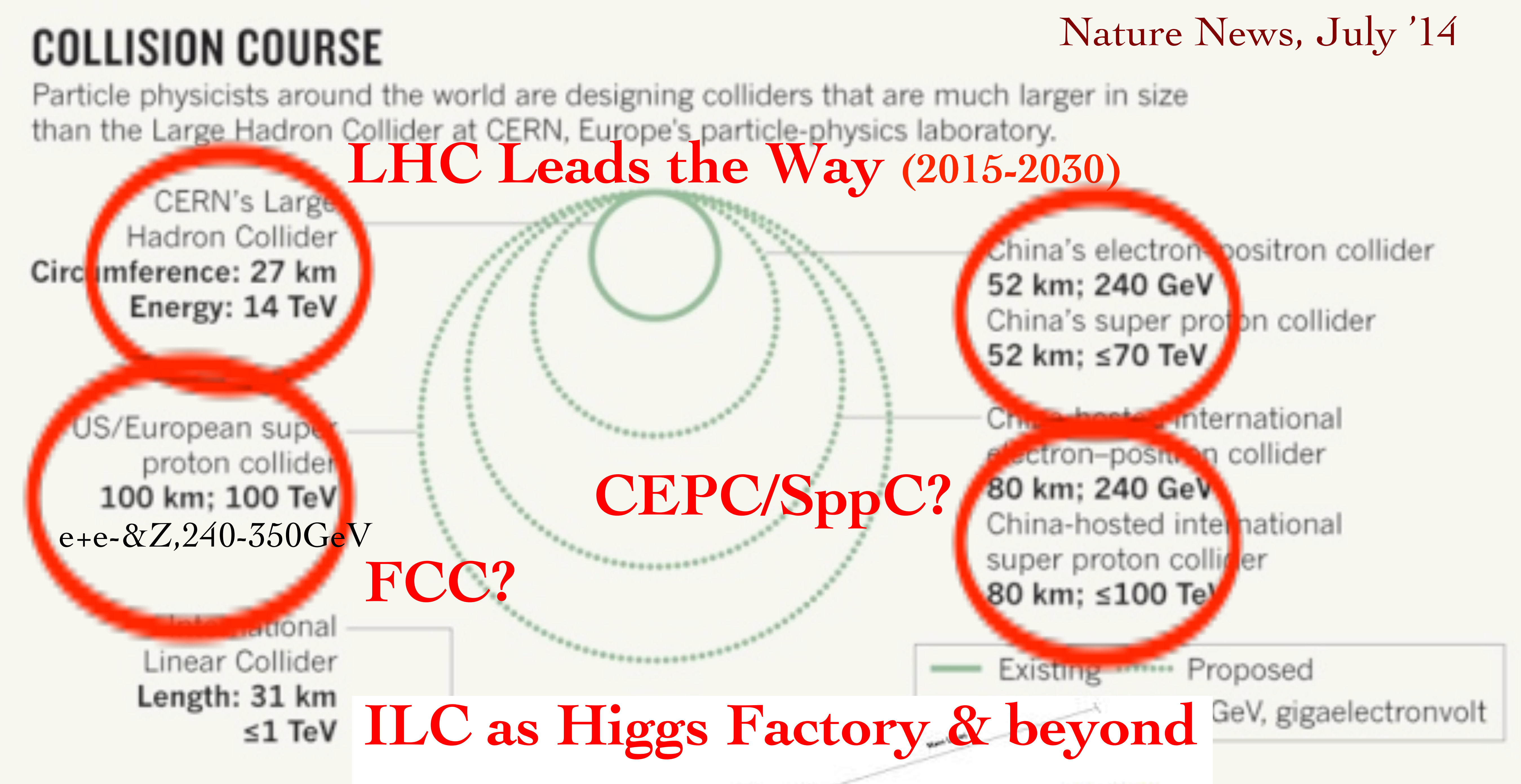


TH, Z.Liu, A.Natarajan, arXiv:1303.3040

Nature News, July '14



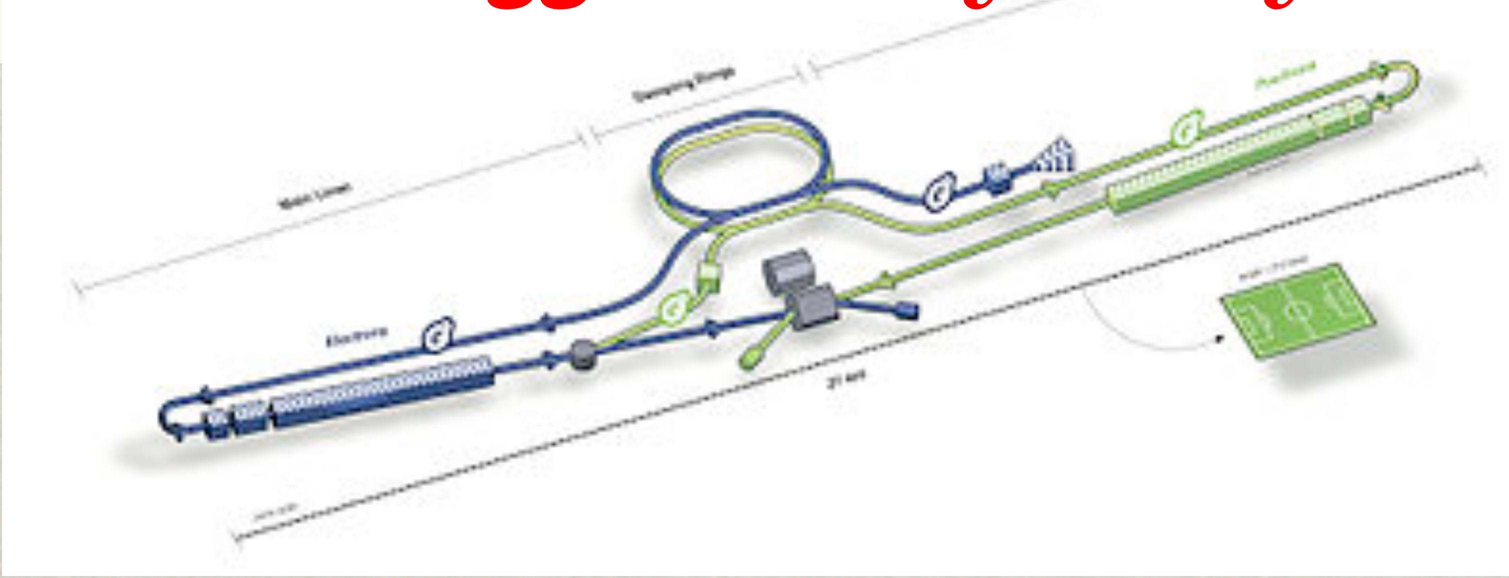
LHC Leads the Way (2015-2030)

e+e-&Z,240-350GeV

CEPC/SppC?

FCC?

ILC as Higgs Factory & beyond



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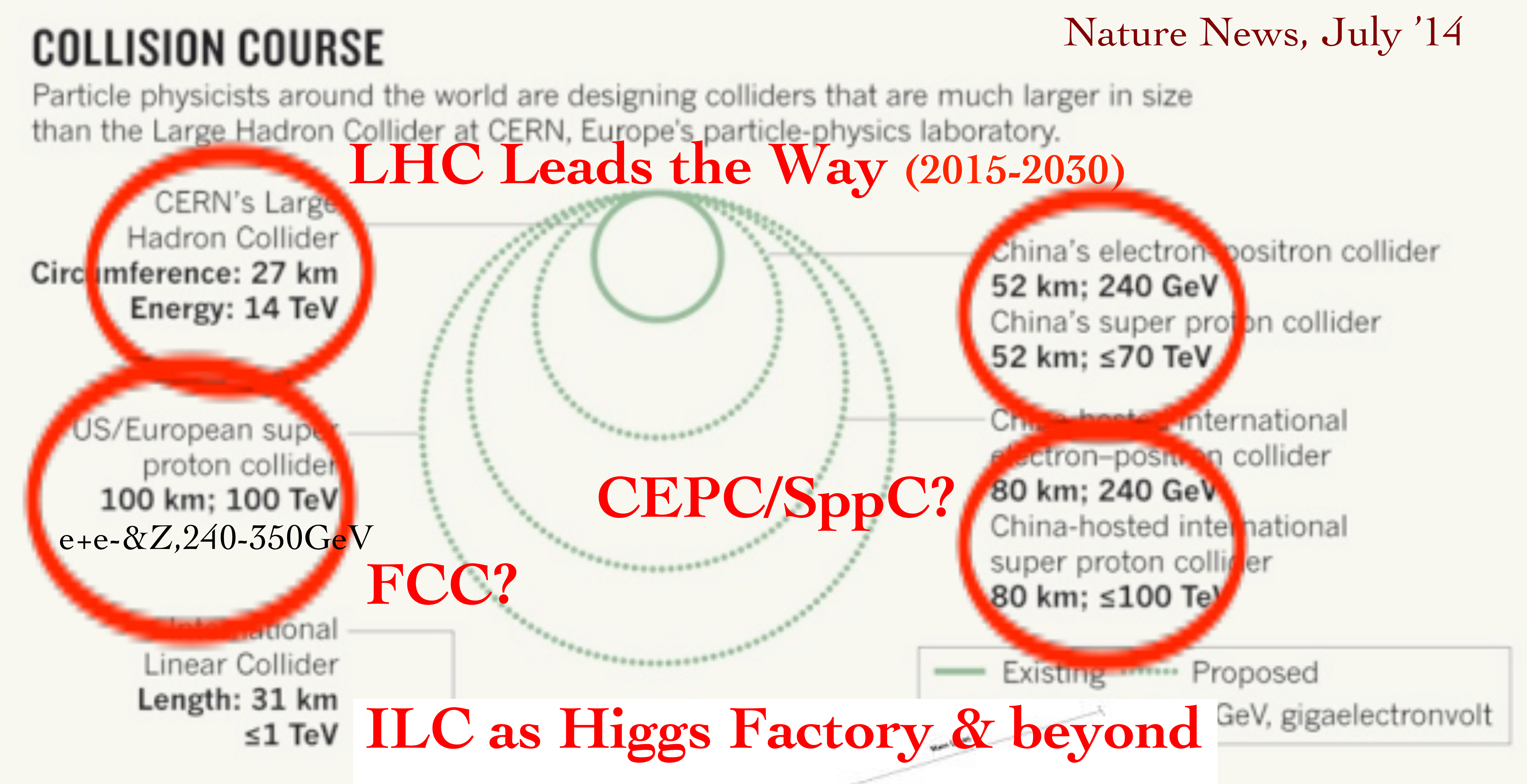


ILC as Higgs Factory & beyond

Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

Snowmass 1310.8361

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int\mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
dt (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

ILC:
(Hitoshi Yamamoto, 2015)

Academic Experts Committee Interim Summary

Recommendation 1: The ILC project requires huge investment that is so huge that a single country cannot cover, thus it is indispensable to share the cost internationally. From the viewpoint that the huge investments in new science projects must be weighed based upon the scientific merit of the project, a clear vision on the discovery potential of new particles as well as that of precision measurements of the Higgs boson and the top quark has to be shown so as to bring about novel development that goes beyond the Standard Model of the particle physics.

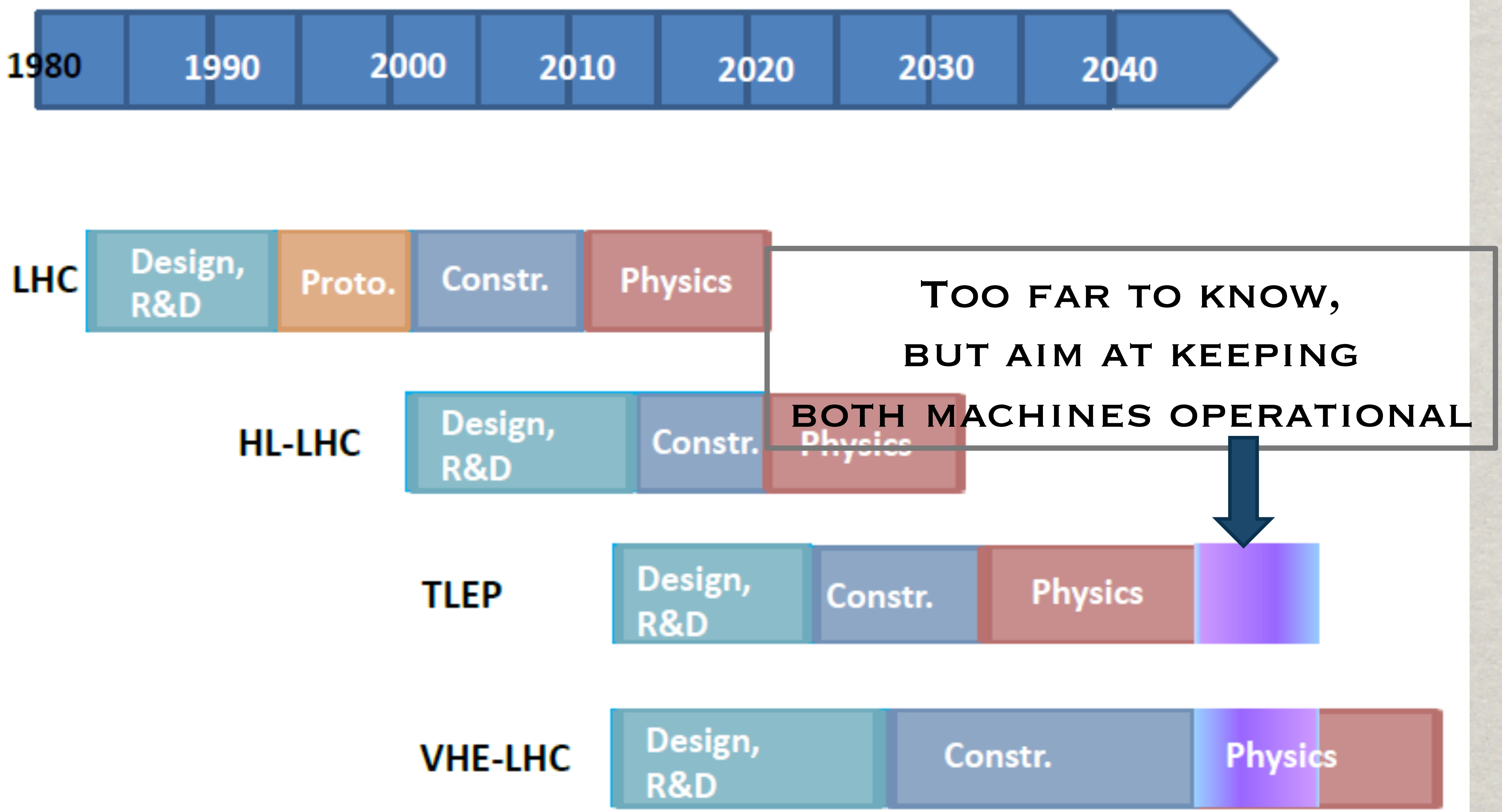
Recommendation 2: Since the specifications of the performance and the scientific achievements of the ILC are considered to be designed based on the results of LHC experiments, which are planned to be executed through the end of 2017, it is necessary to closely monitor, analyze and examine the development of LHC experiments. Furthermore, it is necessary to clarify how to solve technical issues and how to mitigate cost risk associated with the project.

Recommendation 3: While presenting the total project plan, including not only the plan for the accelerator and related facilities but also the plan for other infrastructure as well as efforts pointed out in Recommendations 1 & 2, it is important to have general understanding on the project by the public and science communities.

TLEP/VHE-LHC:

F. Zimmermann

possible long-term time line



CEPC/SPPC:

Yifang Wang

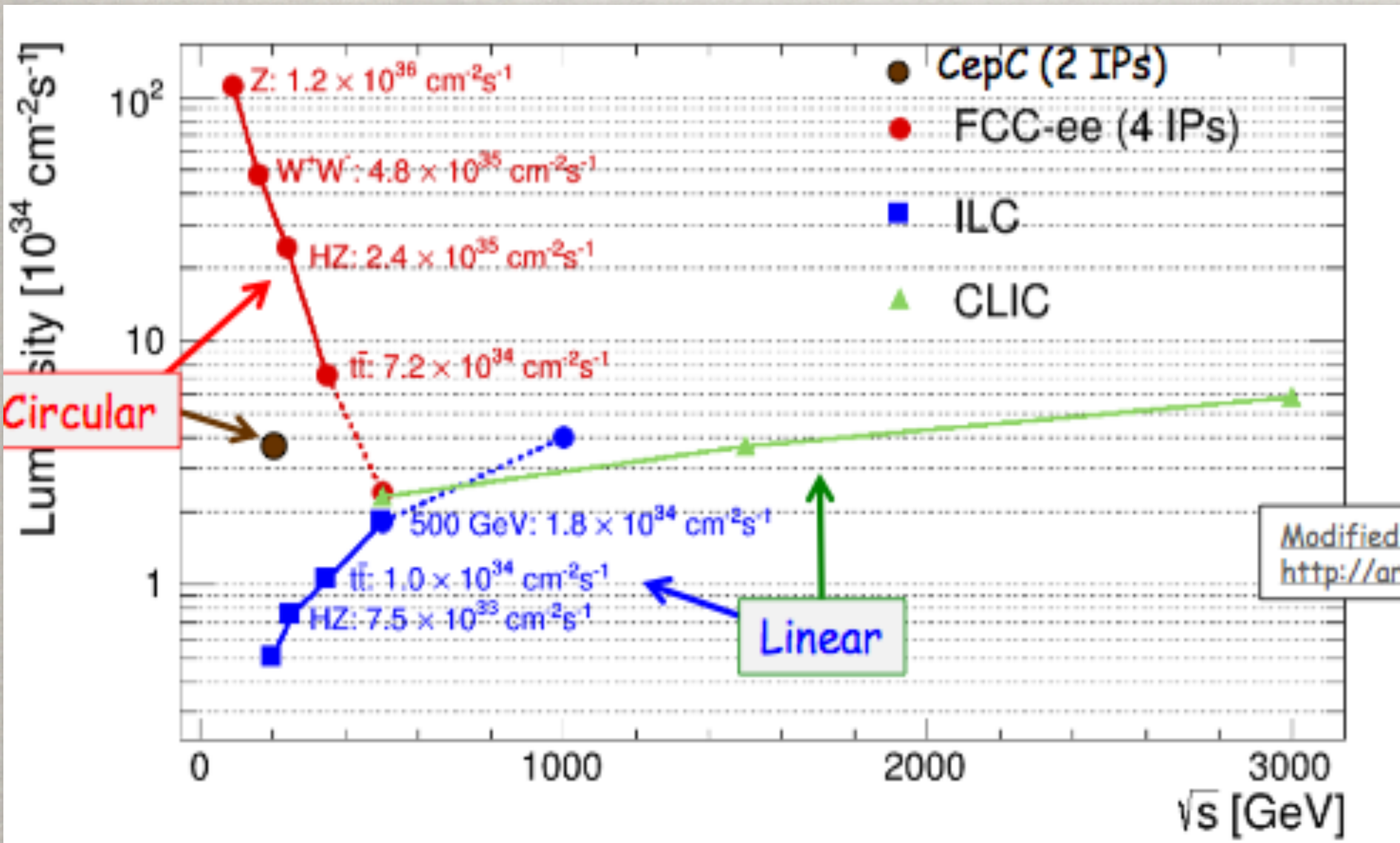
(理想的) 时间进度安排

技术上

- **CEPC（建设：2021-2028）**
  - 预先研究及准备工作
    - 2014年底之前完成 pre-CDR，争取纳入十三五规划
    - 预研：2016-2020
    - 工程设计: 2016-2020
  - 建设: 2021-2027
  - 数据获取: 2028-2035
- **SppC（建设：2035-2042）**
  - 预先研究及准备工作
    - 预先研究：2014-2030
    - 工程设计: 2030-2035
  - 建造: 2035-2042
  - 数据获取: 2042 - 2055

显然具体过程不会如此简单，应该有：
概念设计评审
预研项目申请与审批
项目建议书评审
工程设计评审
国际评审
。。。

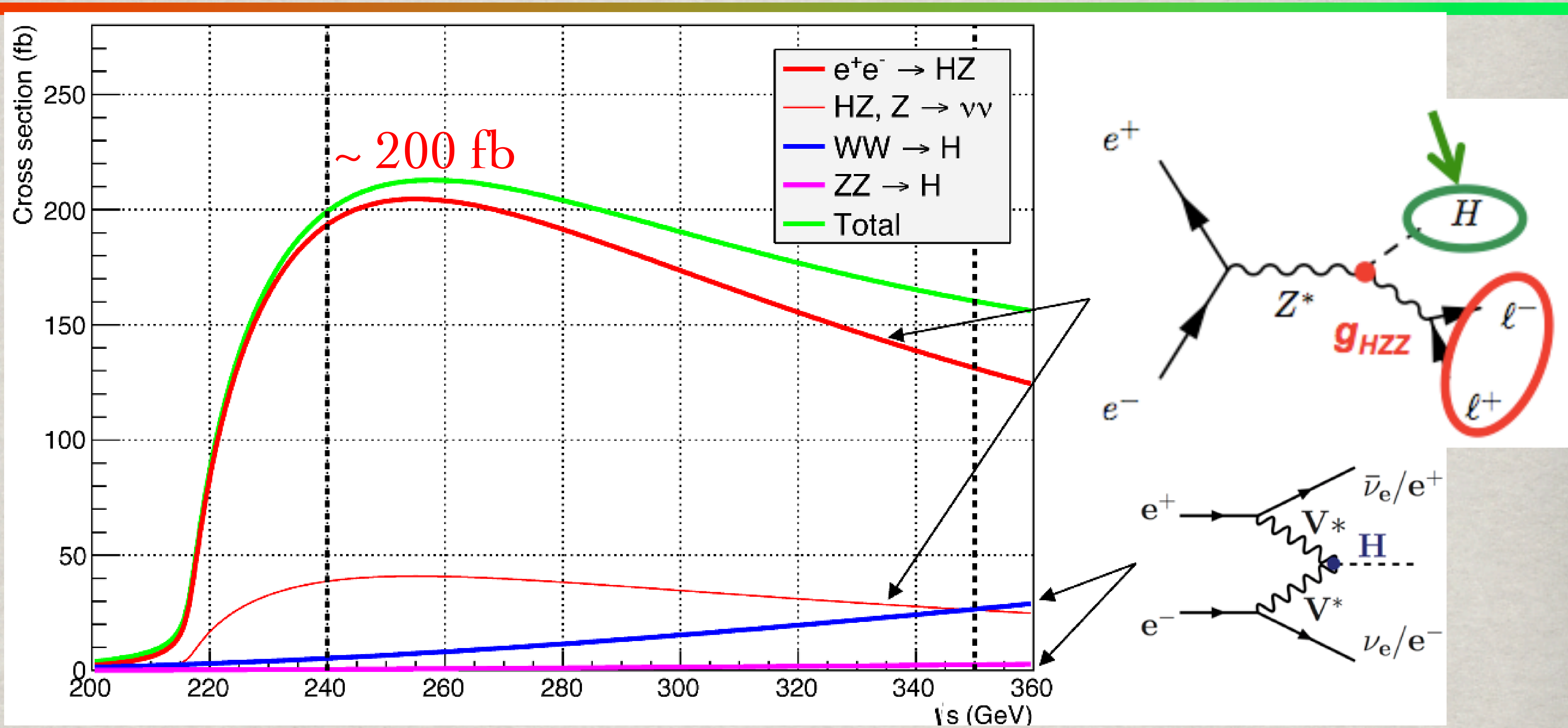
e^+e^- colliders: Energy/Lumi projection



TLEP Report: 1308.6176

E_{cm}	running time	statistics (FCC-ee)
	b,c,τ	10^{11} b,c,τ
90 GeV	1-2 yrs	10^{12} Z (Tera Z)
160 GeV	1-2 yrs	10^{8}- 10^{9} WW(Oku W)
240 GeV	4-5 yrs	2×10^{6} ZH (Mega H)
350 GeV	4-5 yrs	10^{6} tt (Mega top)

Higgs-Factory: Mega (10^6) Higgs Physics



ILC Report: 1308.6176

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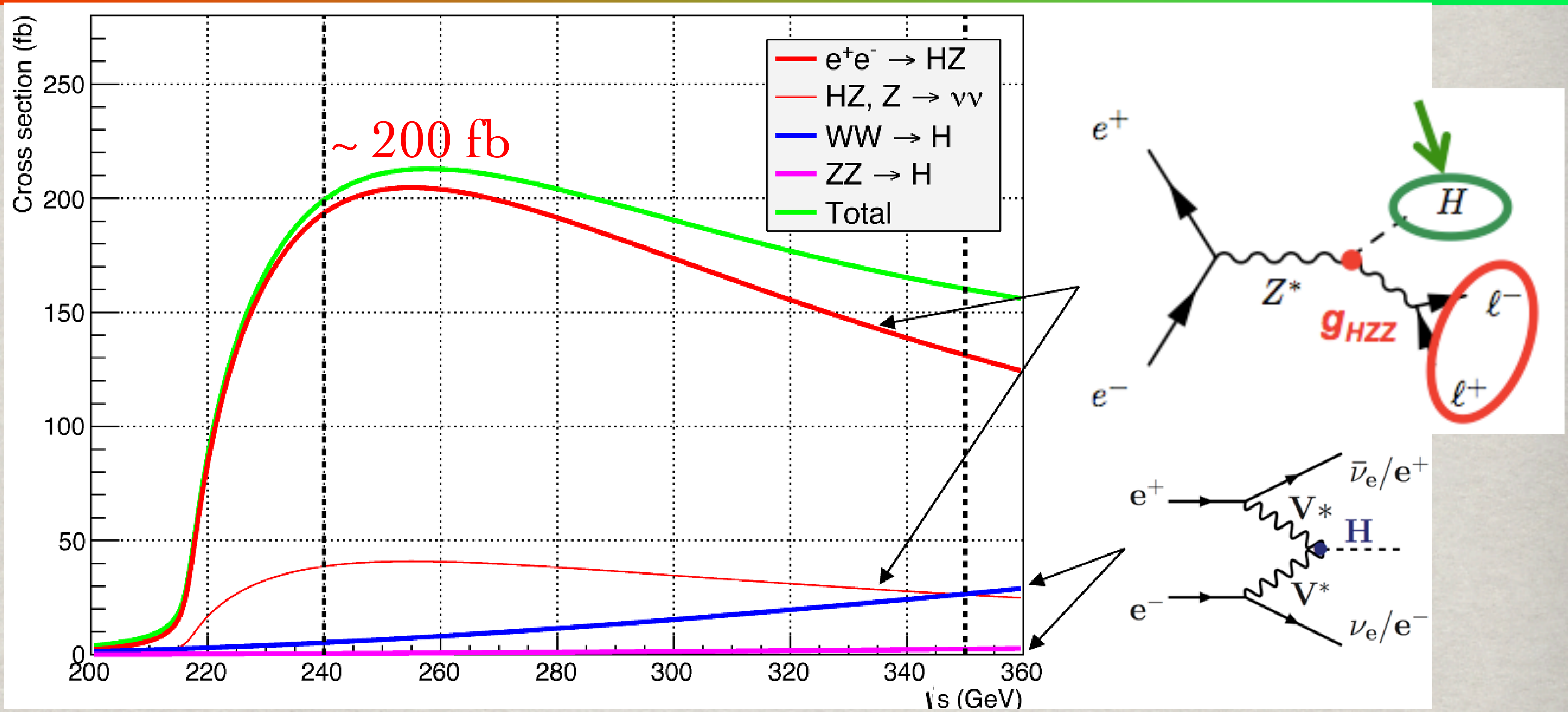


ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

- Model-independent measurement: ILC Report: 1308.6176

  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

  (HL-LHC: assume SM, $\Gamma_H \sim 5\text{-}8\%$, $\Delta m_H \sim 50$ MeV)
- TLEP 10^6 Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

TLEP Report: 1308.6176

• Comparison (FCC_{ee}/TLEP 4IP)

Snowmass Higgs Working Group: 1310.8361

Coupling	HL-LHC	ILC	FCC-ee
k_W	2-5%	1.2%	0.19%
k_Z	2-4%	1.0%	0.15%
k_b	4-7%	1.7%	0.42%
k_c	–	2.8%	0.71%
k_τ	2-5%	2.4%	0.54%
k_μ	~10%	91%	6.2%
k_g	2-5%	8.4%	1.5%
k_γ	3-5%	2.3%	0.8%
k_{Zg}	~12%	?	?
BR_{invis}	~10-15%?	< 0.9%	< 0.19%
Γ_H	~50%?	5.0%	1.0%
k_t	7-10%	14%	13% (*)
k_H	30-50% ?	80%	80%(*)

Model-independent results
HL-LHC(3 ab^{-1}),
ILC(0.25,0.5,1 ab^{-1}), TLEP(10 ab^{-1})

Sensitive to new physics at tree level
Expected effects < 5% / Λ^2_{NP}

Sensitive to new physics in loops

Sensitive to light dark matter; exotic decays

Need higher energies

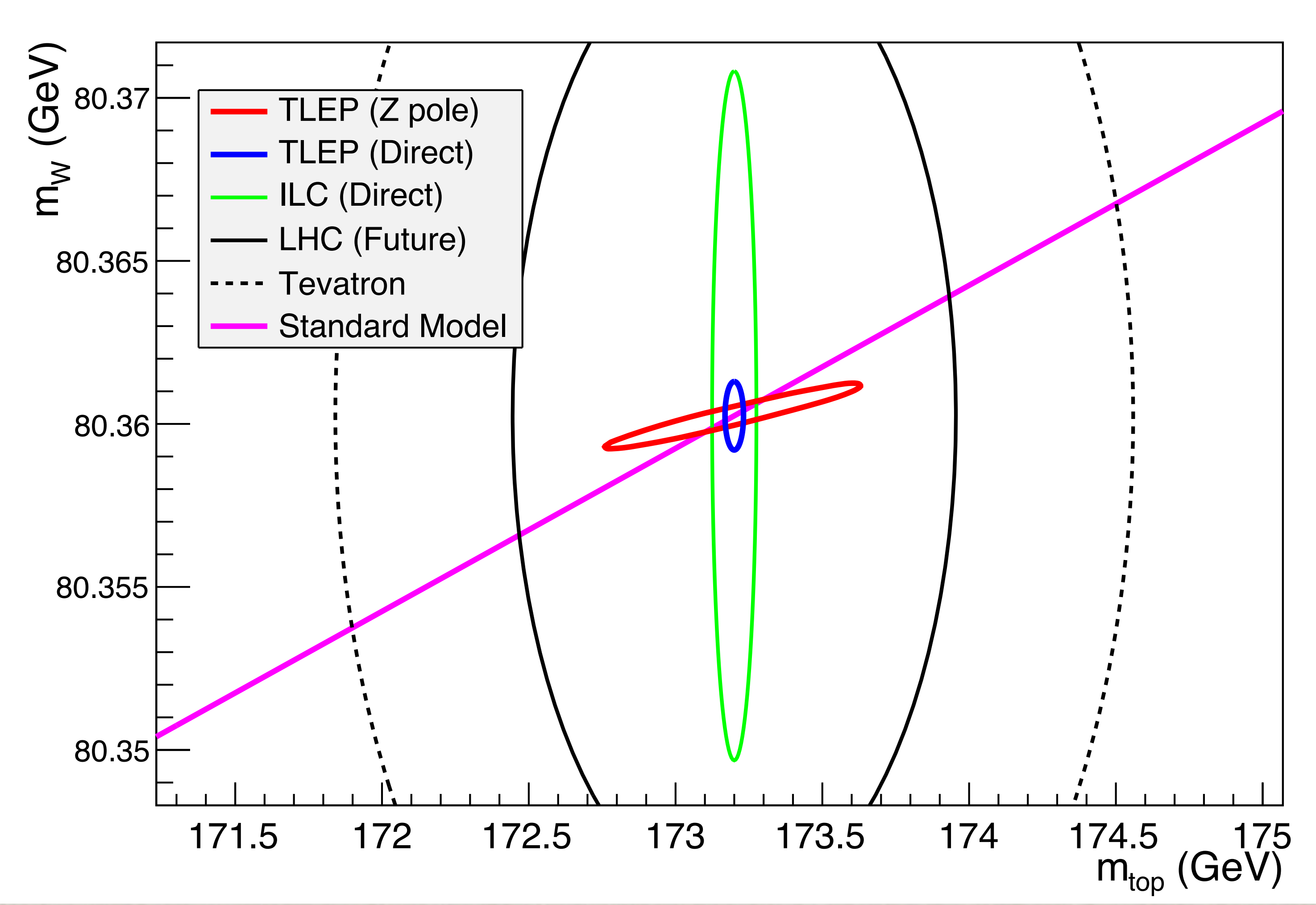
Z-Factory: Tera (10^{12}) Z Physics

TLEP Report: 1308.6176

- Clean environment, ΔE_{cm} < 1 MeV, 10^5 x LEP-I
- possible longitudinal polarization
- Precision measurements (statistical):

Z-ploe: ΔM_Z, $\Delta\Gamma_Z < 0.1$ MeV, $\Delta\sin^2\theta_w < 10^{-6}$;

$\Delta M_W \sim O(1\ \text{MeV})$, $\Delta m_t \sim O(10\ \text{MeV})$, $\Delta m_H \sim O(10\ \text{MeV})$.



Z-Factory: Tera (10^{12}) Z Physics

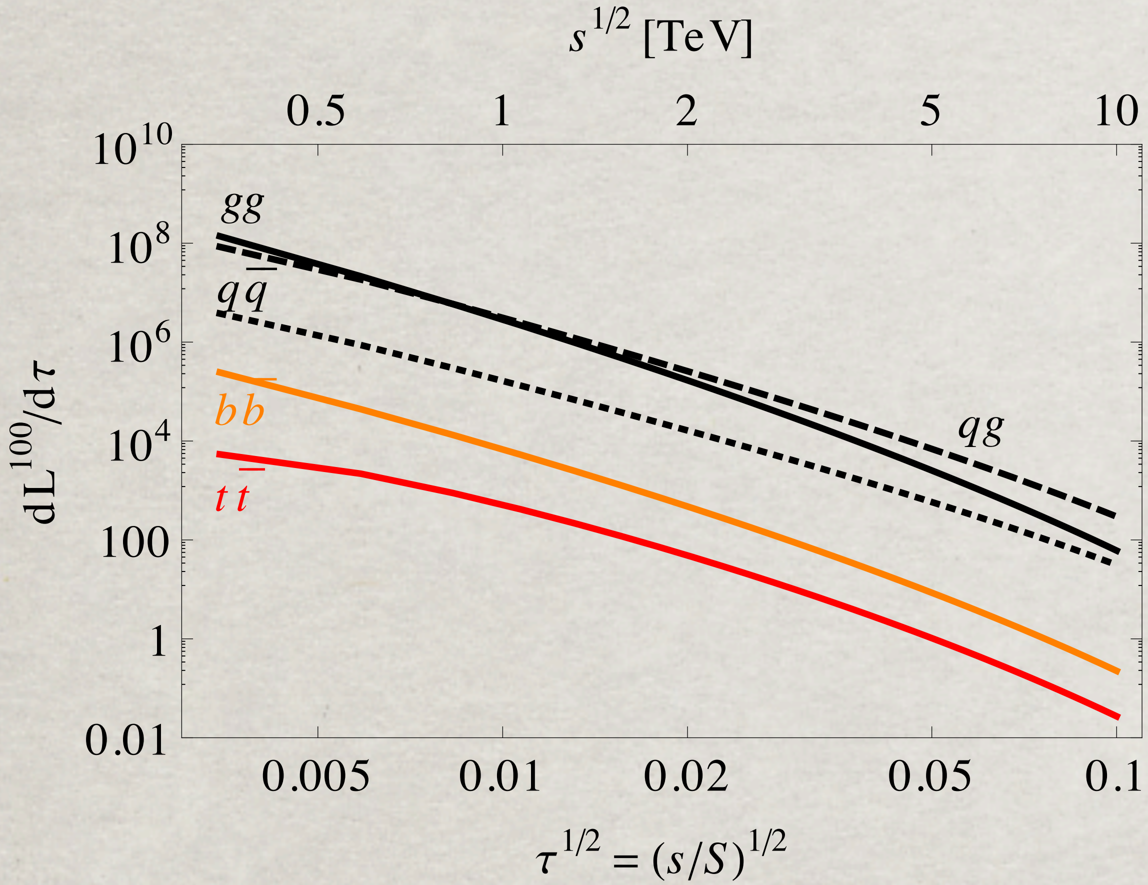
- Flavor physics & CP violation:
  with $O(10^{11})$ B-hadrons: Bs oscillation, Bc …
  complementary to LHCb, Belle II.

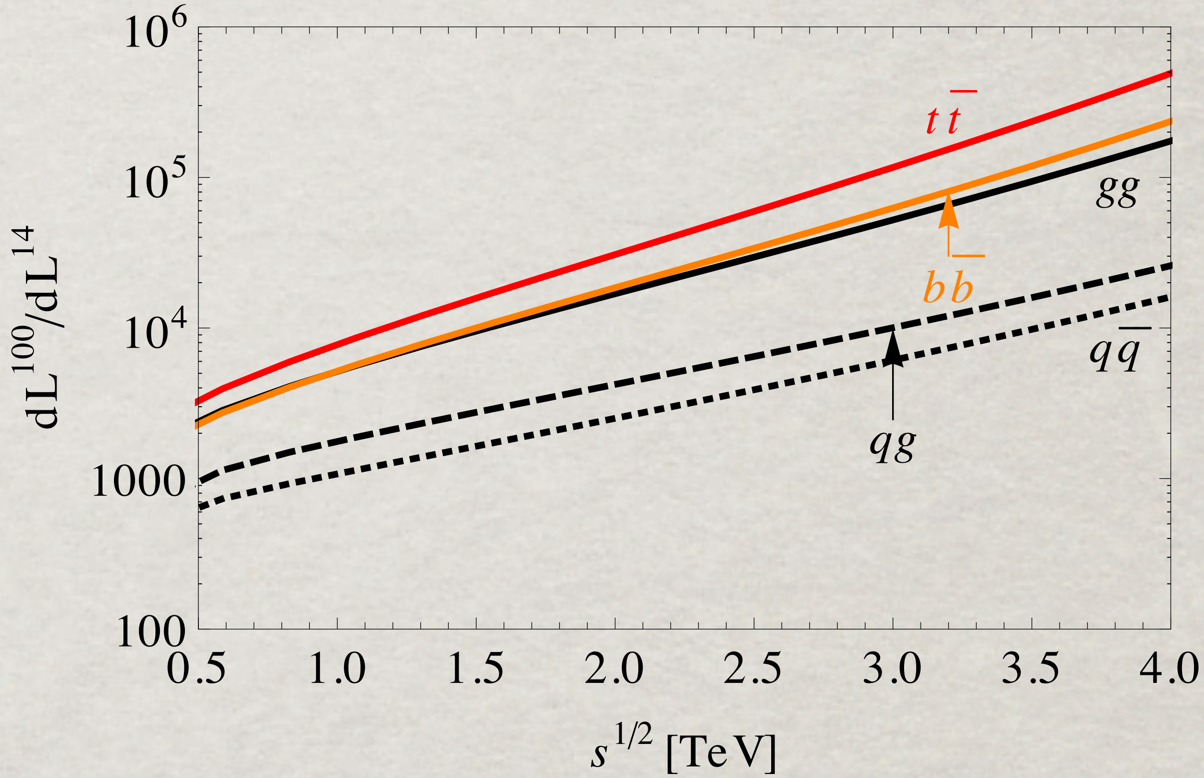
- Indirect new physics probe (Z'…):
  $\delta \sim (v/\Lambda)^2$, sensitivity reach $\Lambda \sim 10$ TeV.

- However, systematics dominance!
  must control theoretical errors!

- It calls for heroic theory efforts:
  largest uncertainty from running α_{QED}
  (low energy hadronic contributions)
  3-loop EW; multi-loop QCD …

The Next Energy Frontier: 100 TeV Hadron Collider





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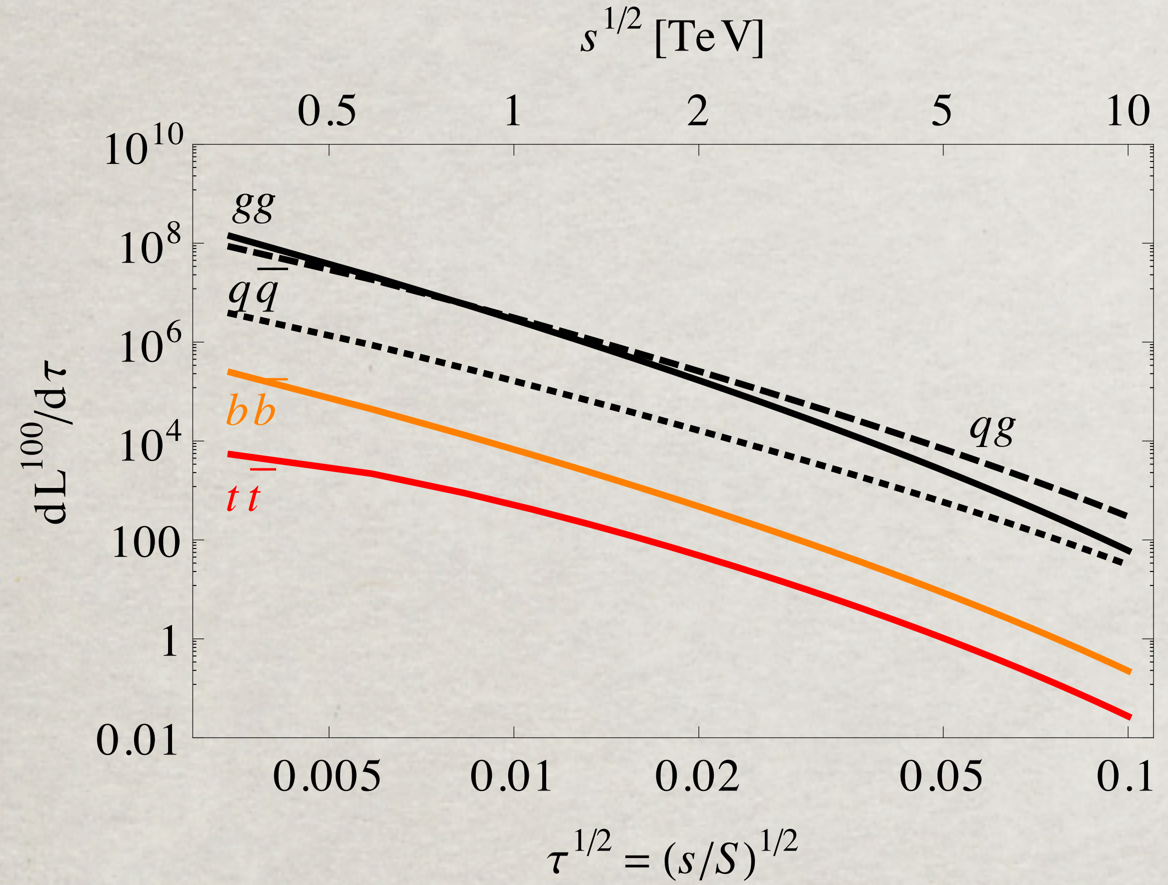
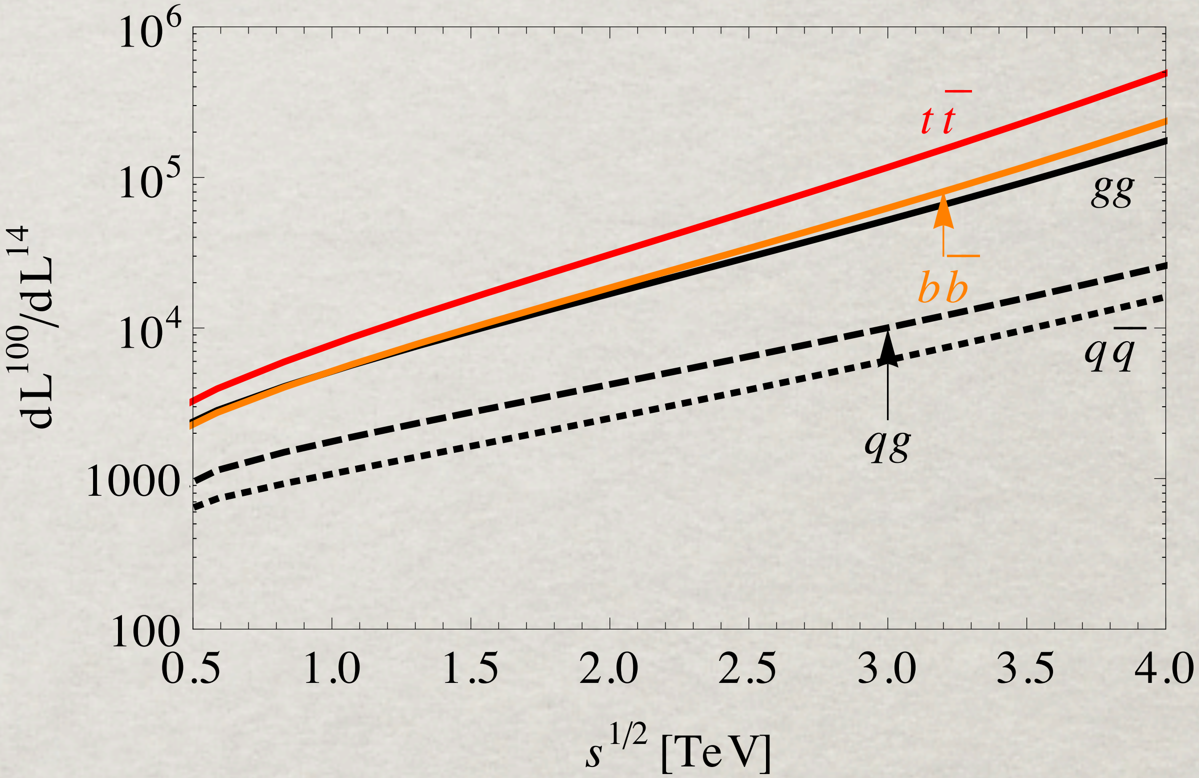
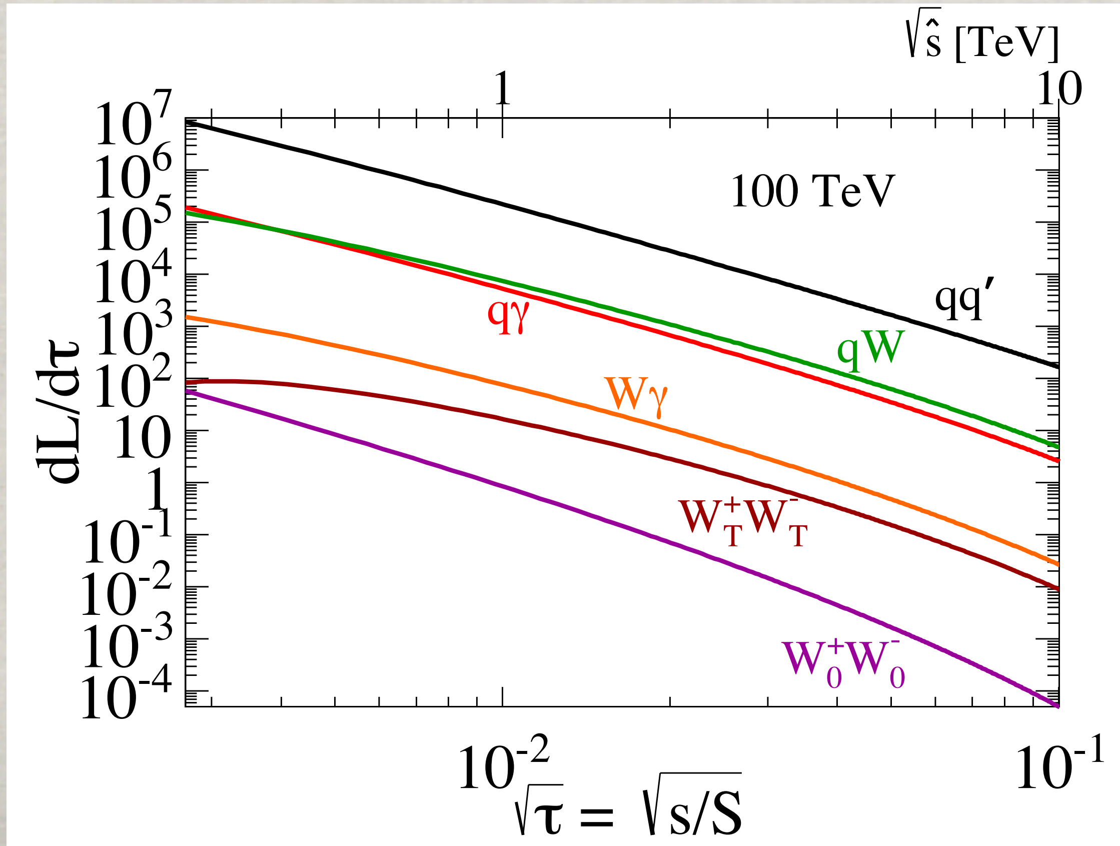
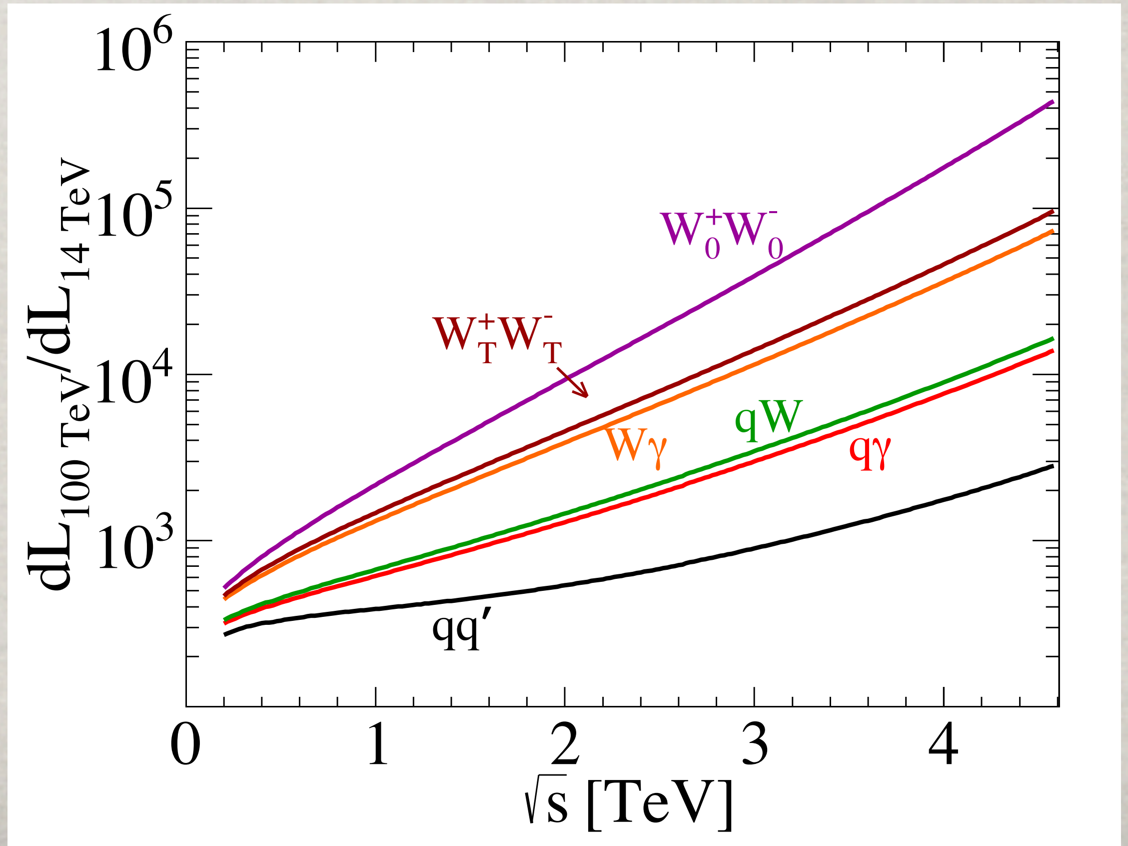
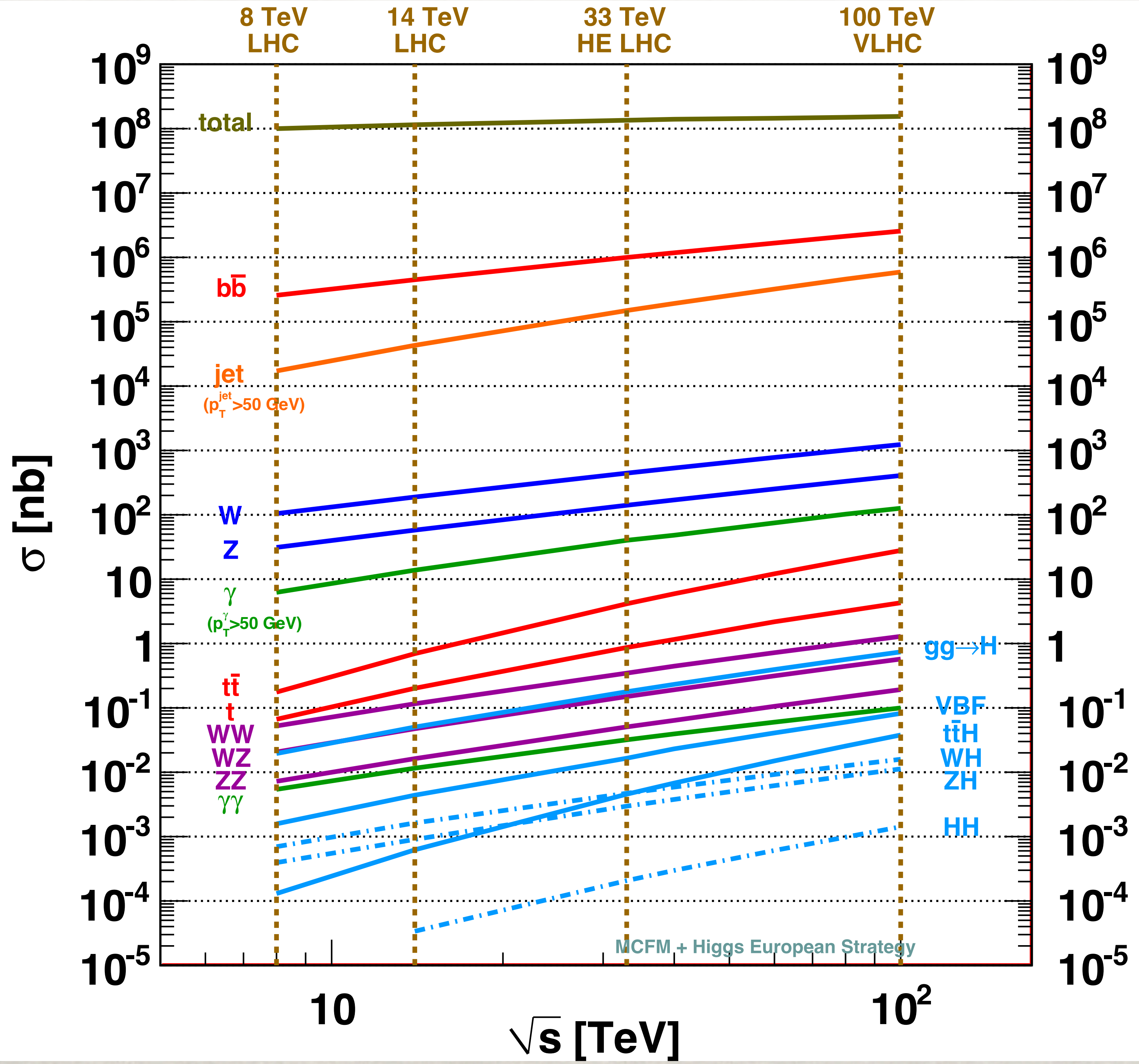








Higgs Production @ FCC_{hh}/SPPC



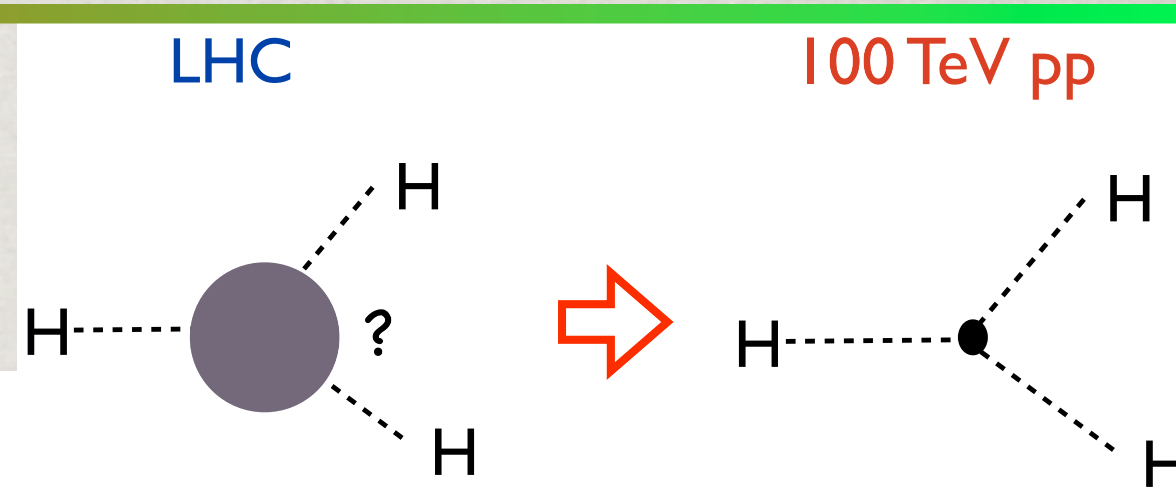
Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

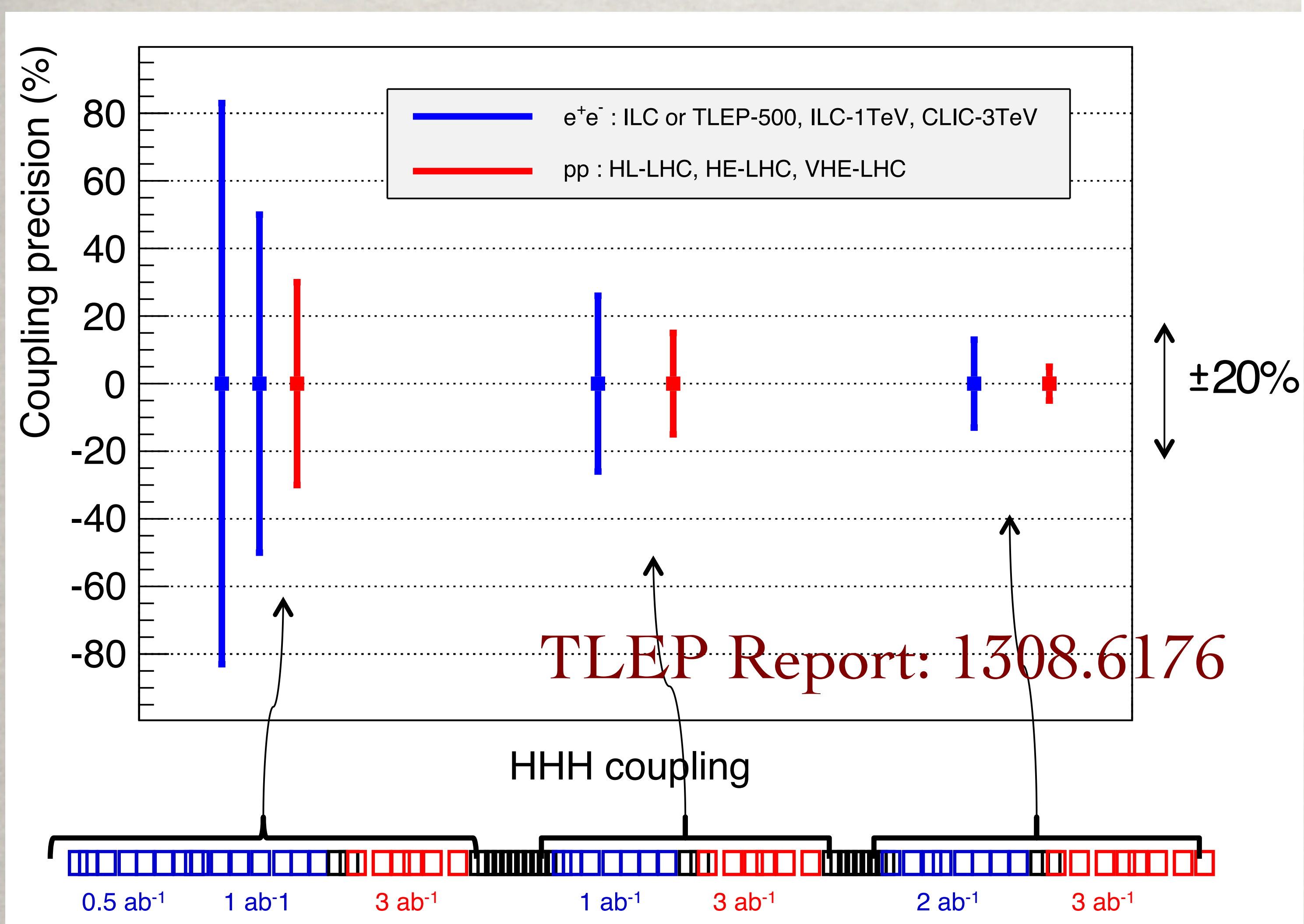
Snowmass QCD Working Group: 1310.5189

Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{HHH}}{3!} H^3 - \frac{g_{HHHH}}{4!} H^4$$

$$g_{HHH} = 6 \;\; v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6 \;\; = \frac{3m_H^2}{v^2}.$$





TLEP Report: 1308.6176

Triple coupling sensitivity:

Test the shape of the Higgs potential, and the fate of the EW-phase transition!

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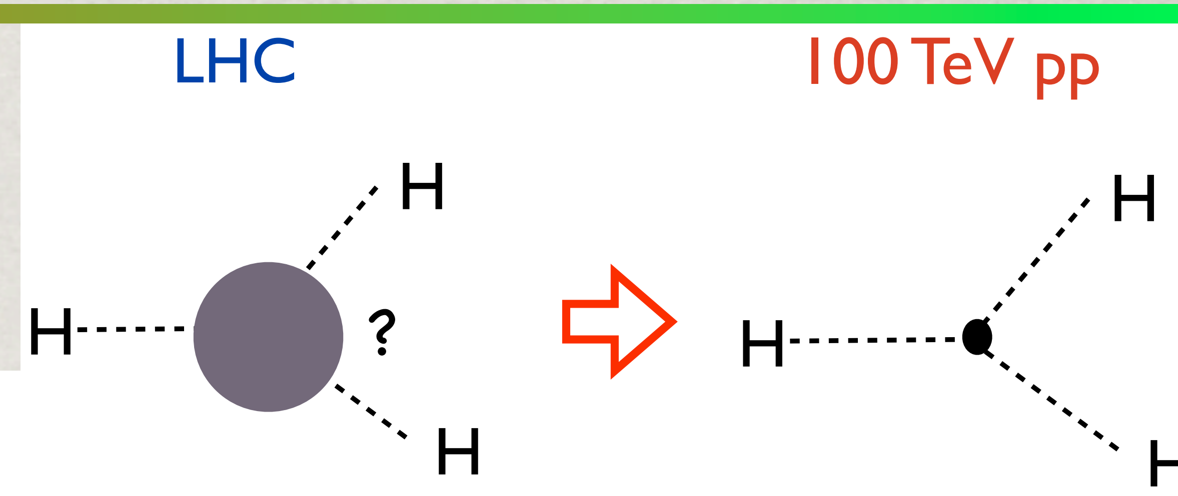
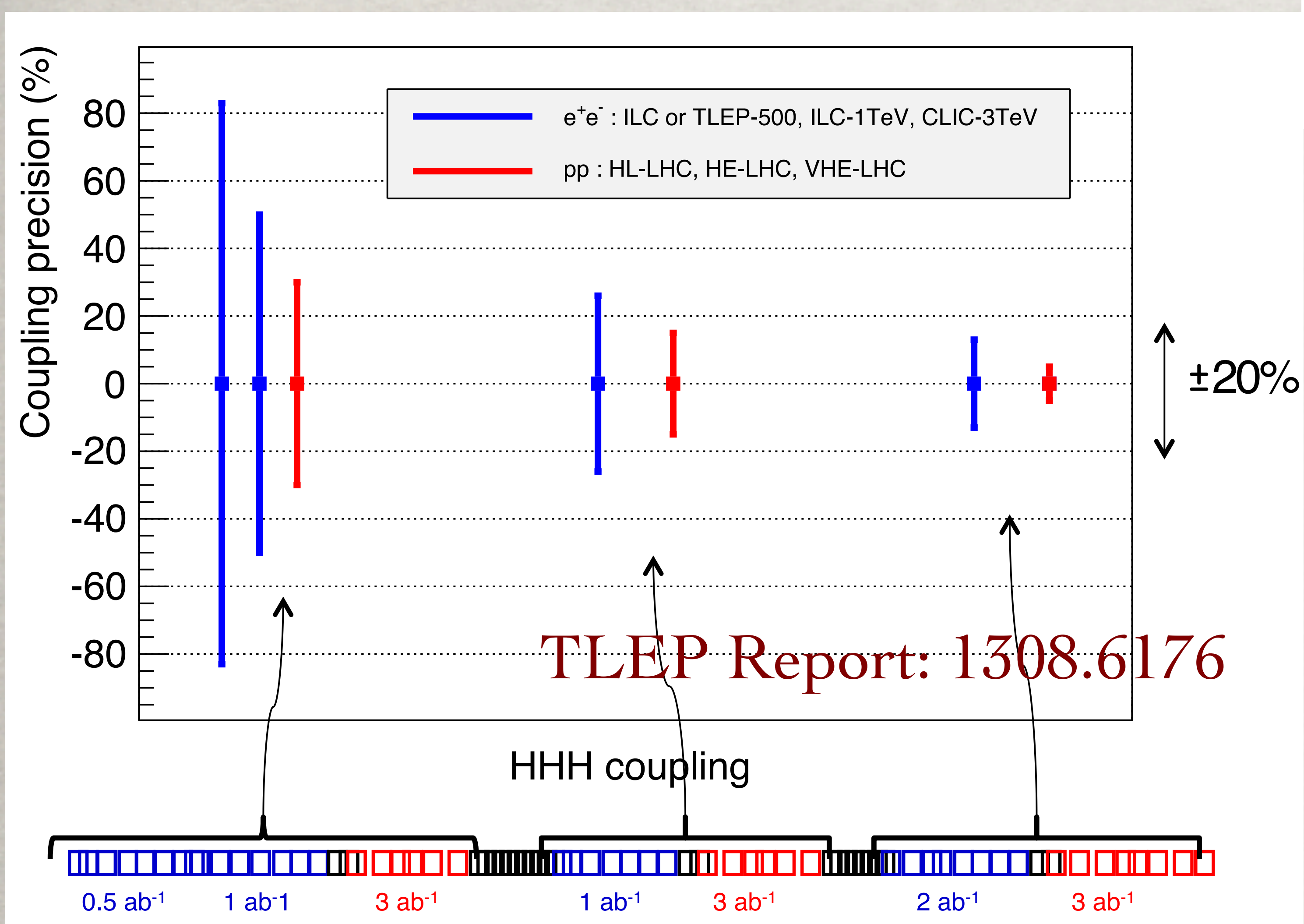




TLEP Report: 1308.6176

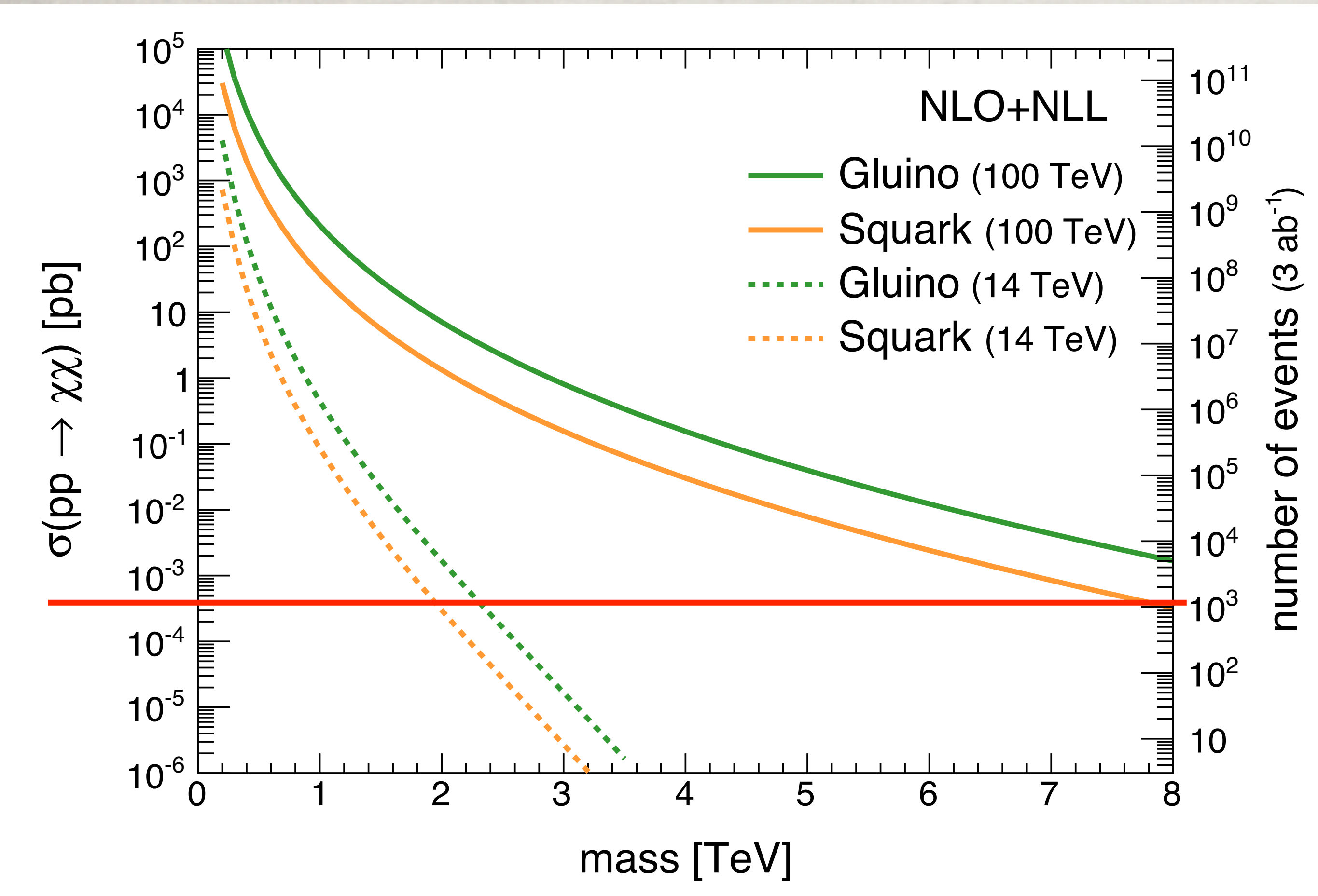
Triple coupling sensitivity:
Test the shape of the Higgs potential, and the fate of the EW-phase transition!

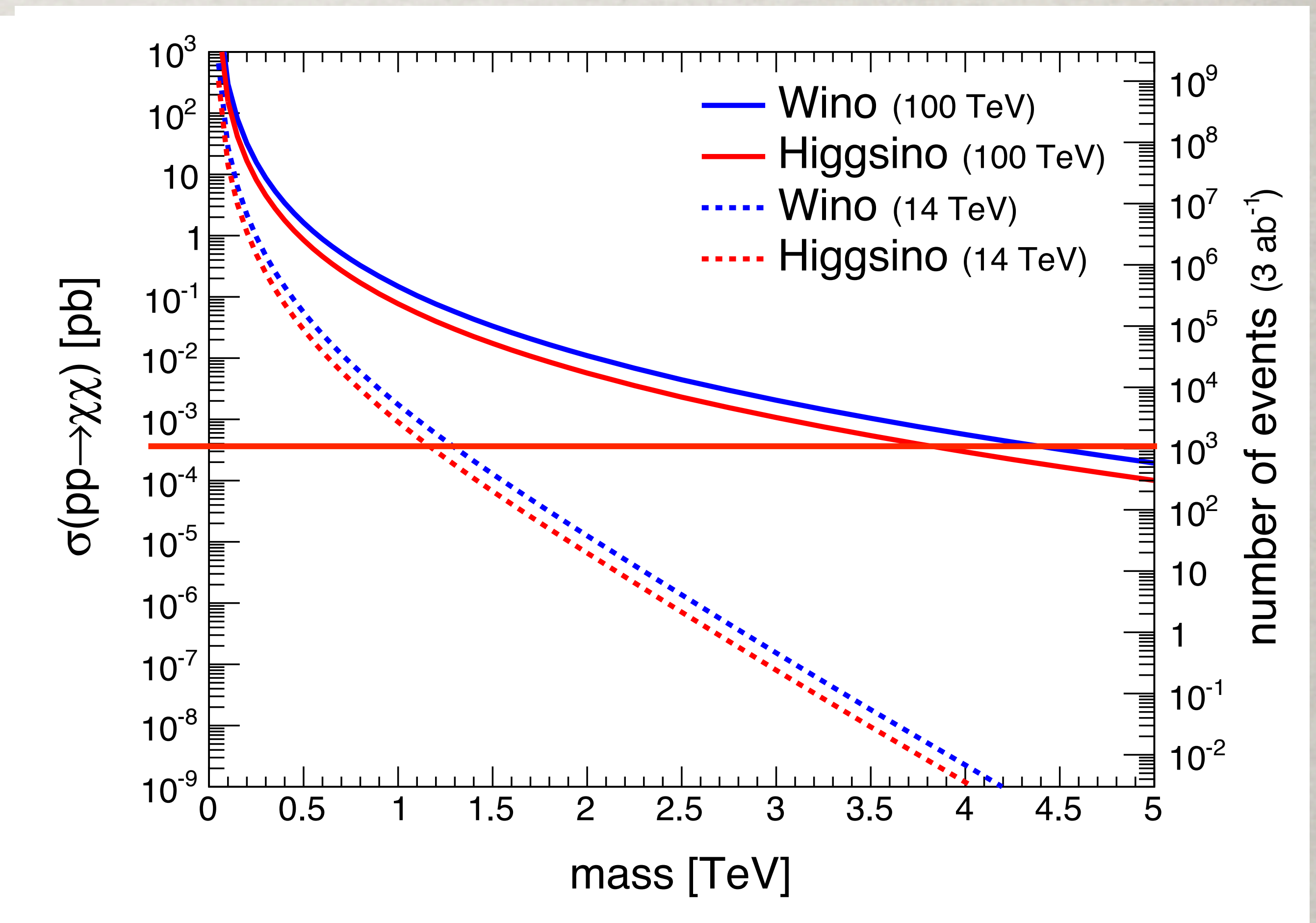
Snowmass 1310.8361

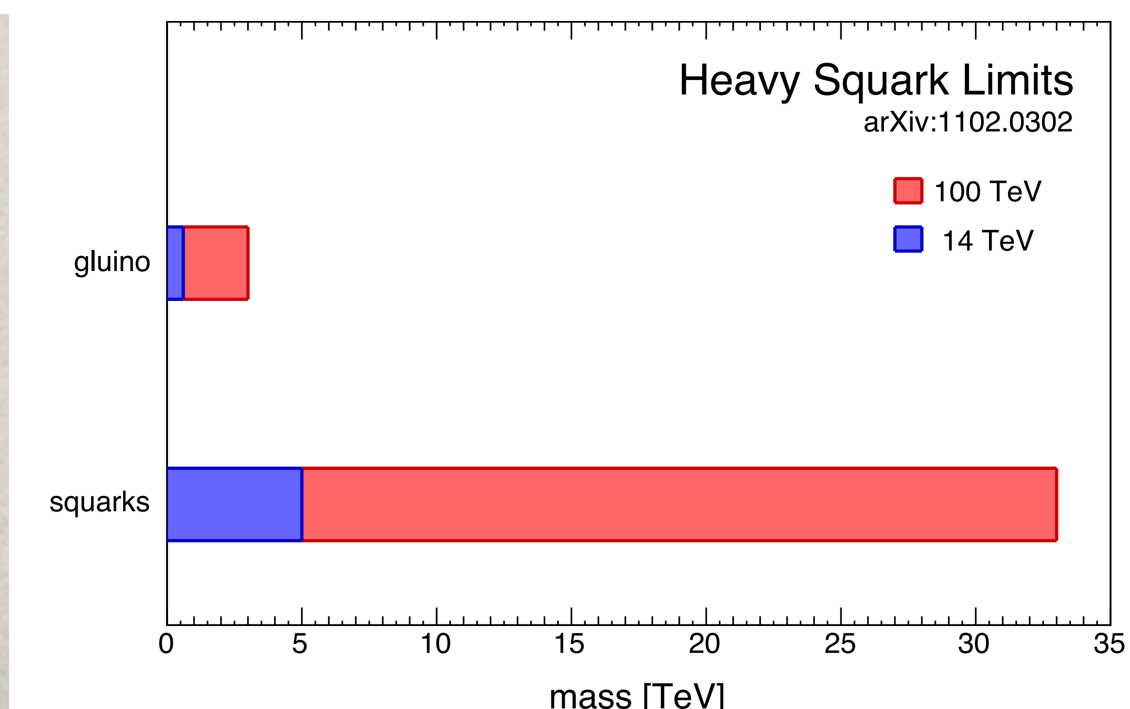
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

SUSY @ FCC$_{hh}$/SPPC

M.Mangano et al.: 1407.5066

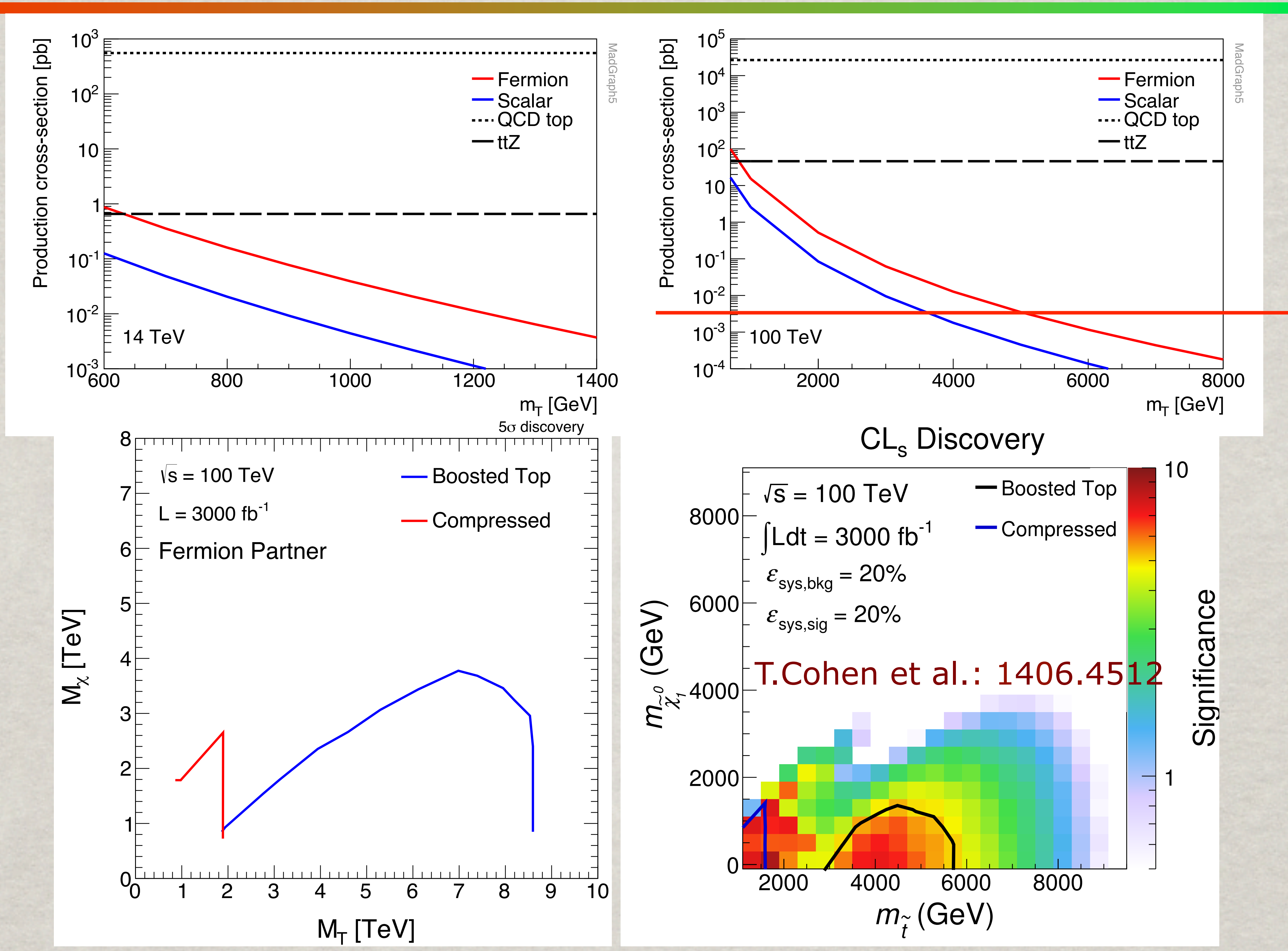






Mass reach at 100 TeV:
~ 7x over LHC

Pushing the "Naturalness" limit



The Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

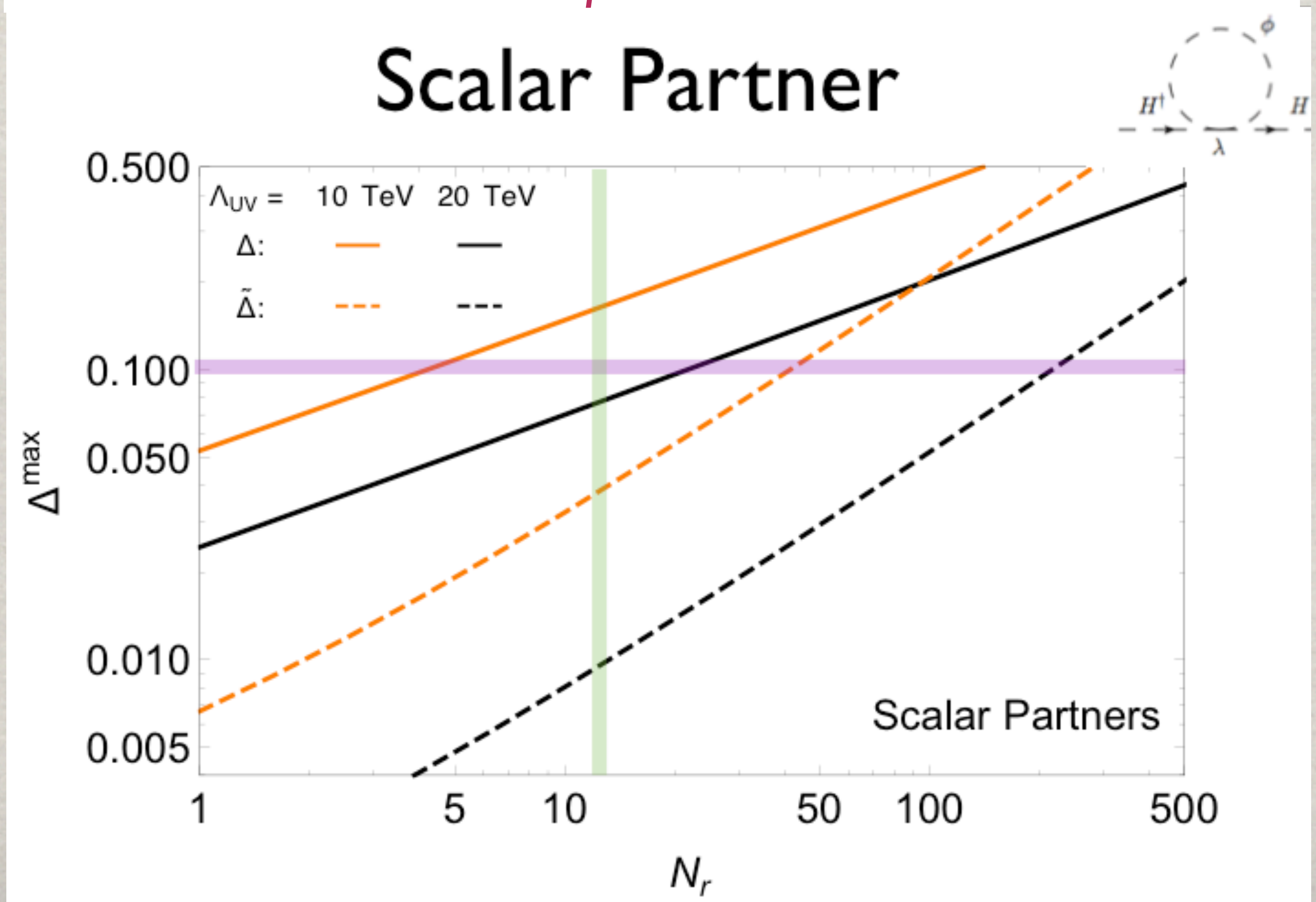
No-Lose(?) for "Natural theory" at FCC$_{ee,hh}$

Irreducible low-E signatures:

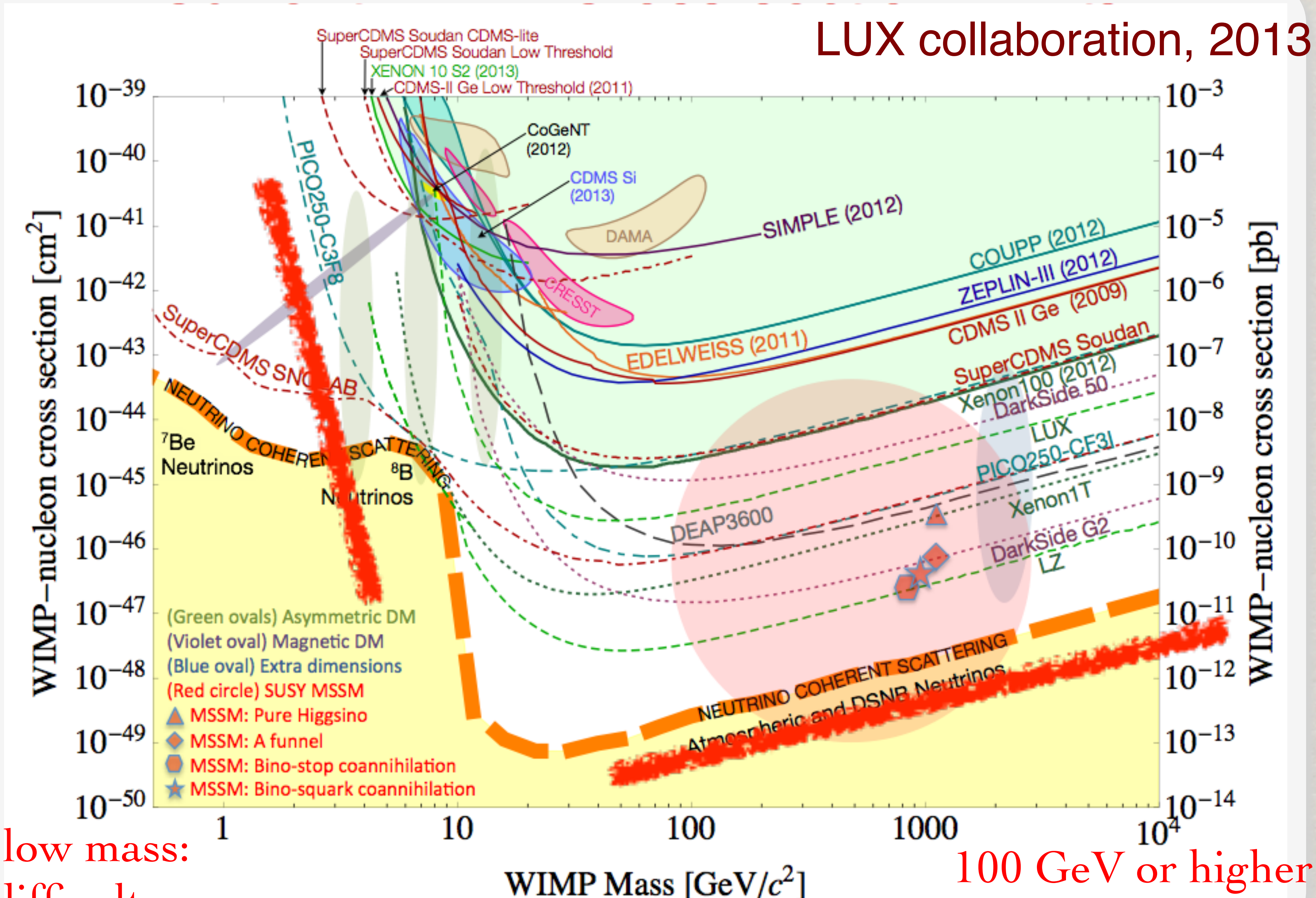
- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)

1509.04284
(David Curtin's talk)

Any theory of ~10% naturalness with O(SM) top partners will be discovered at lepton collider and/or 100 TeV



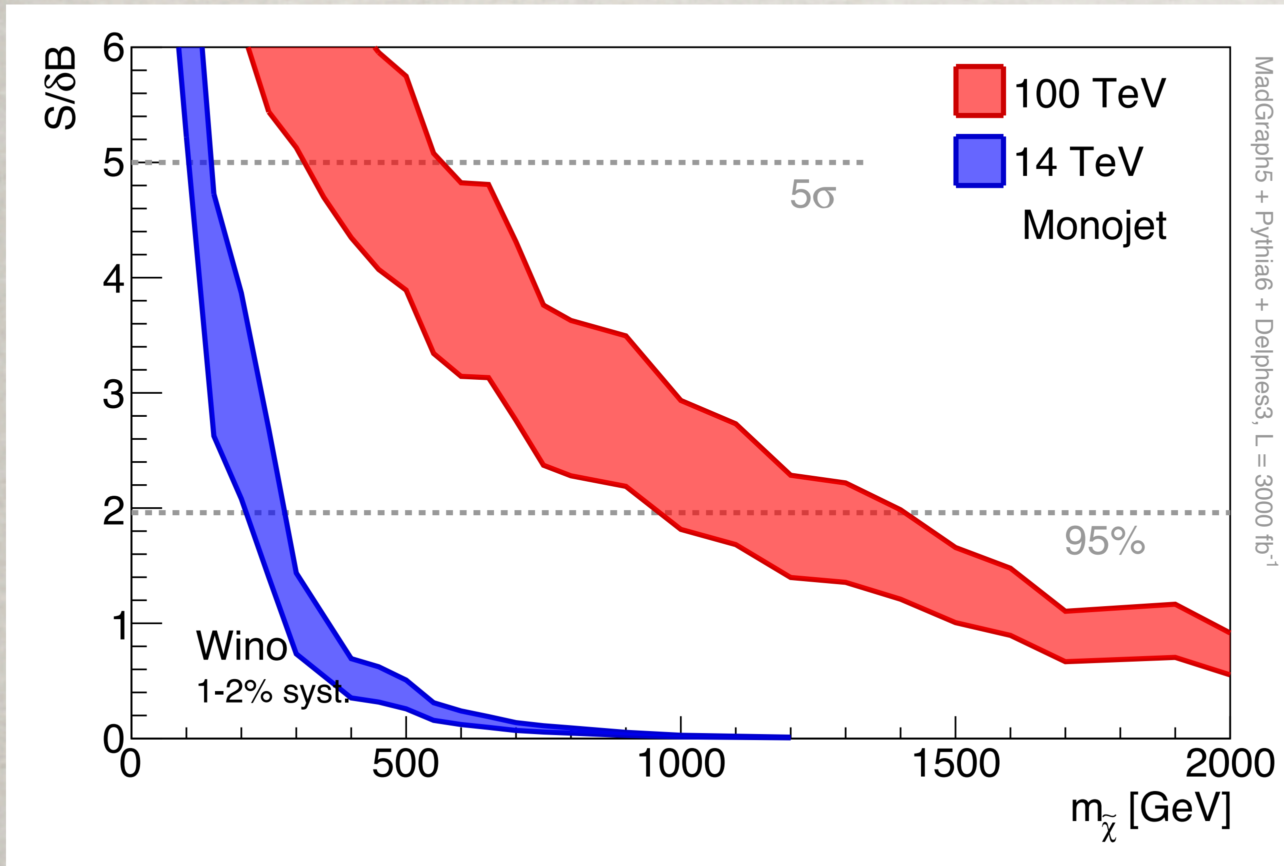
DM Searches

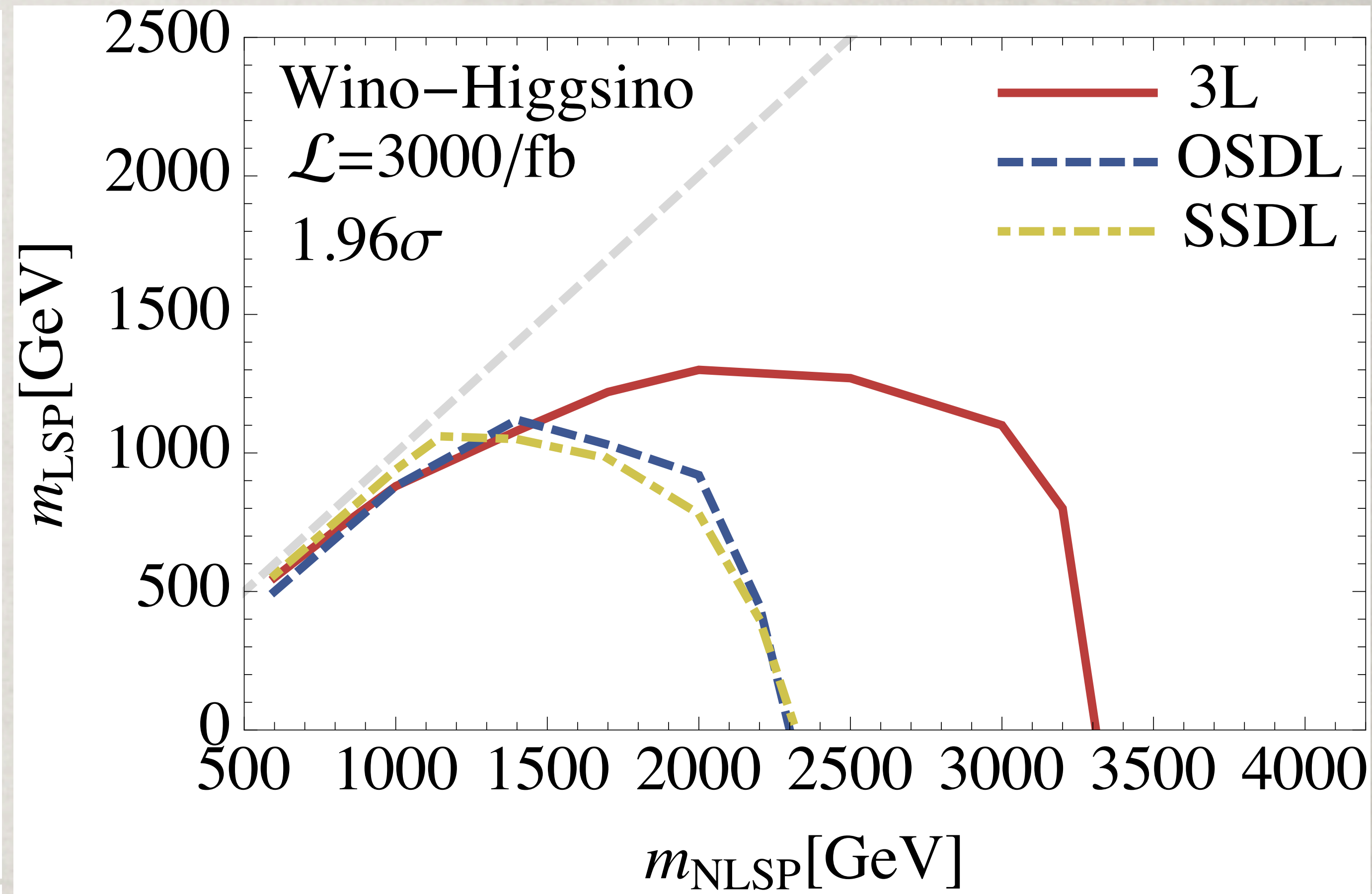


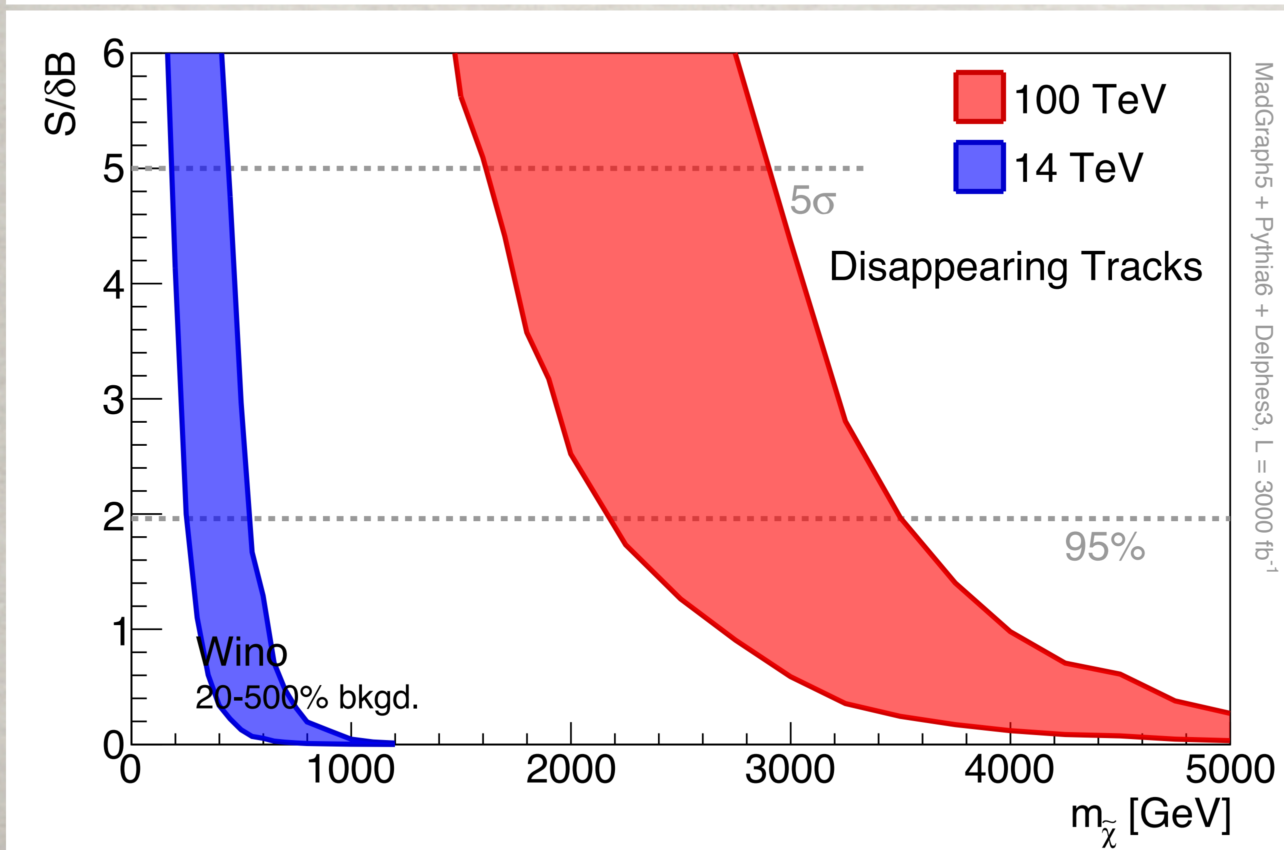
GeV low mass:
DD difficult;
Collider complementary

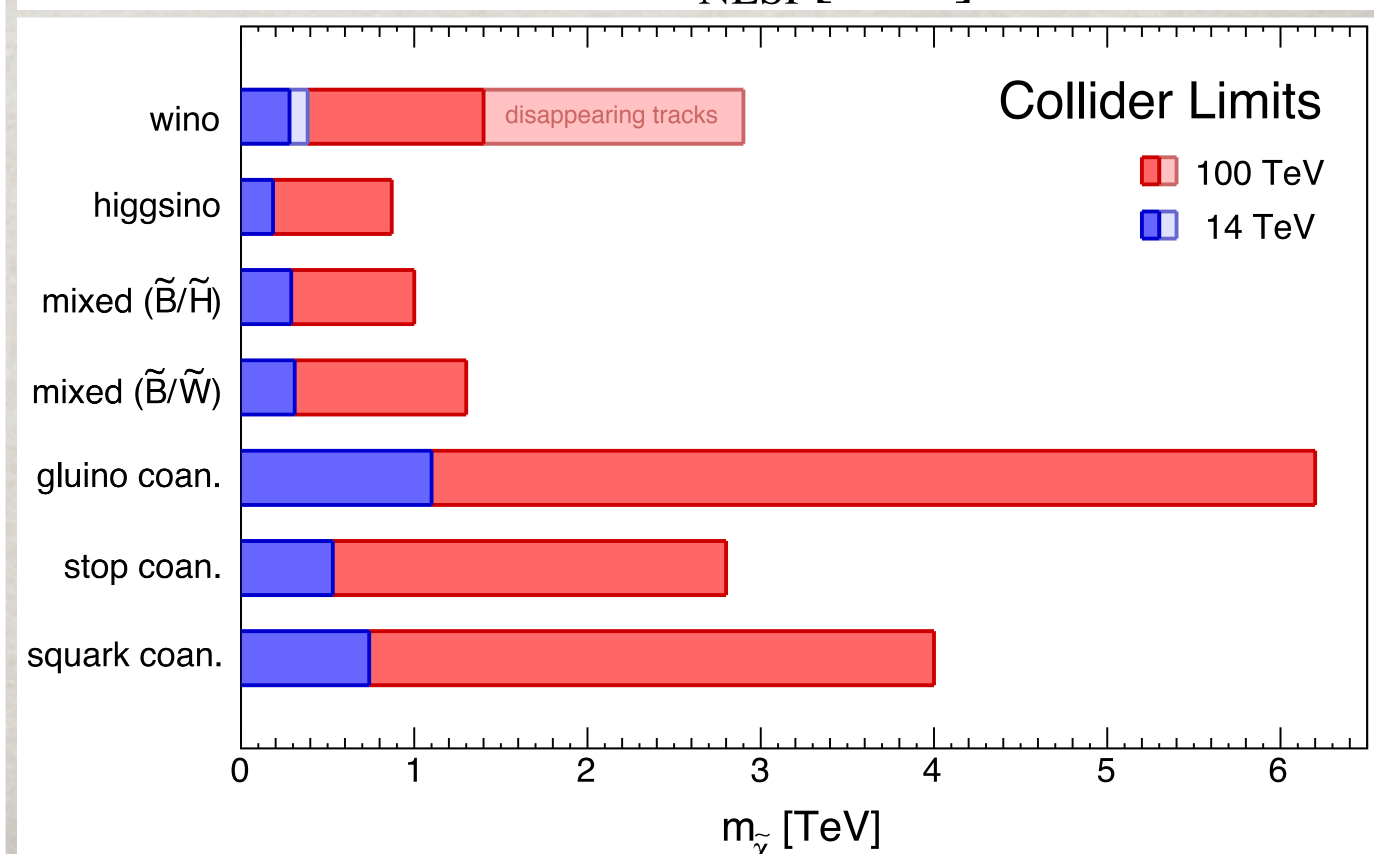
100 GeV or higher mass:
DD + ID + HE Collider

WIMP DM: $M_{\rm DM} < 1.8\ \text{TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$



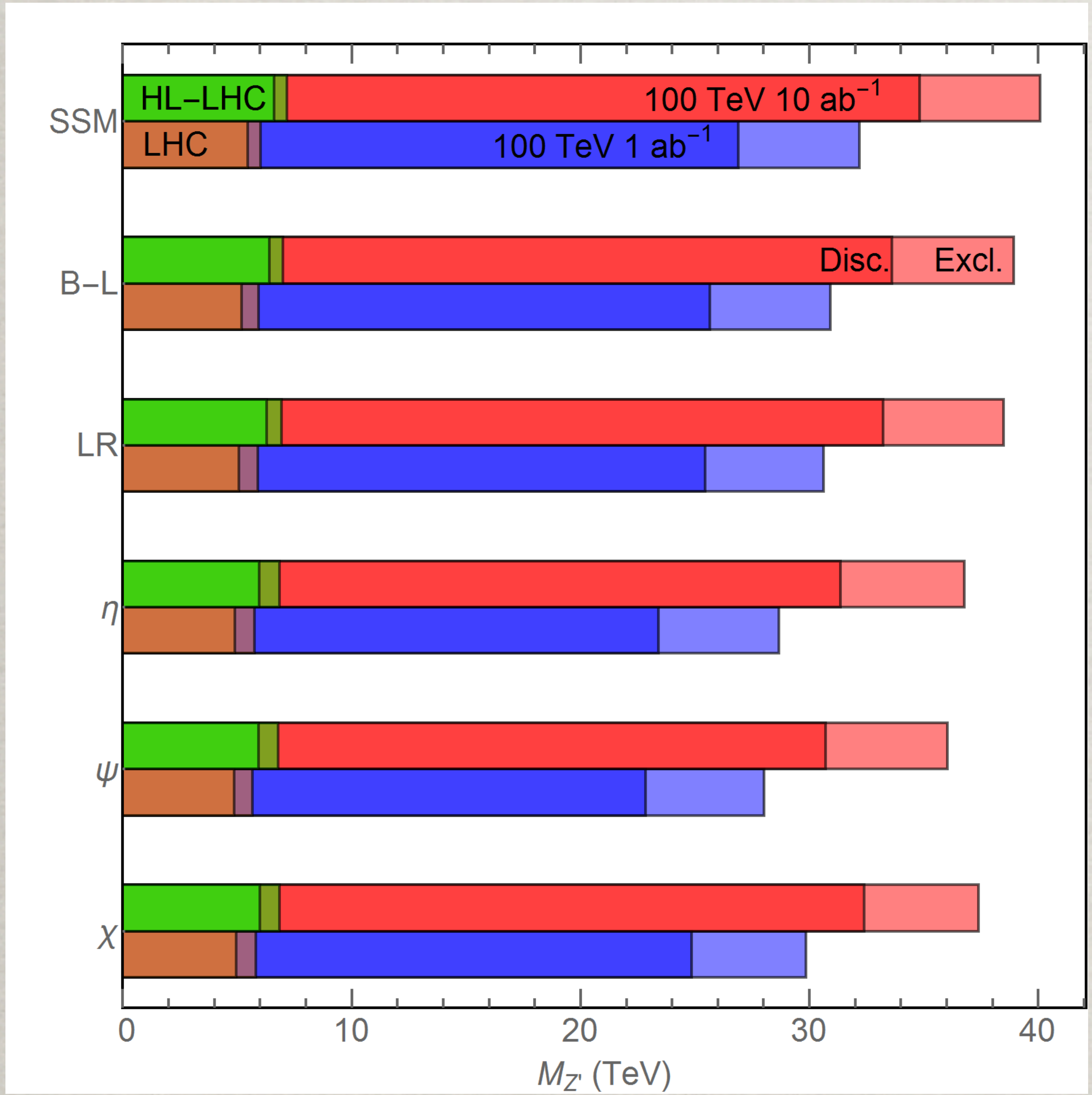






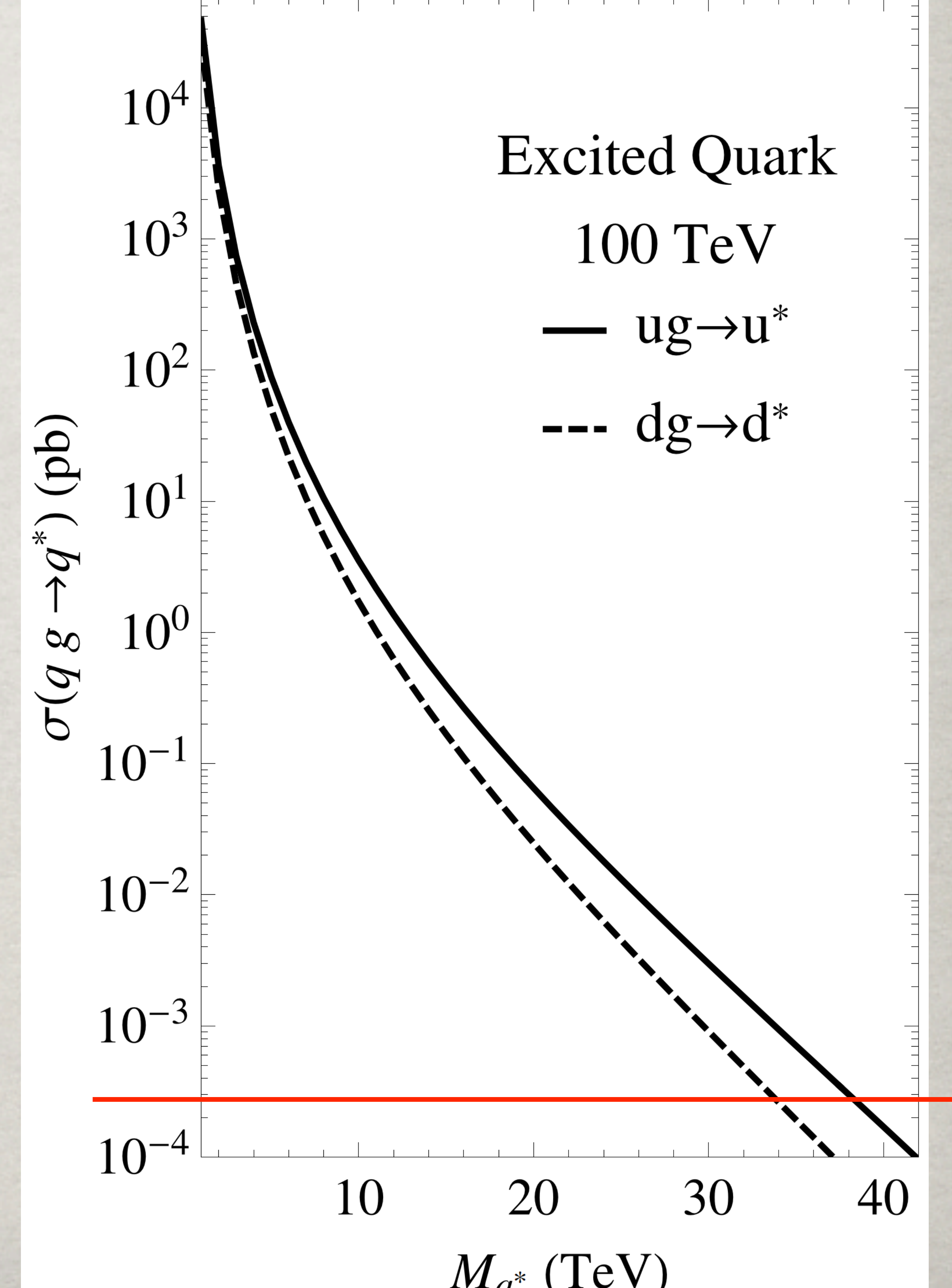
New Particle Searches

Electroweak Resonances: Z',W'



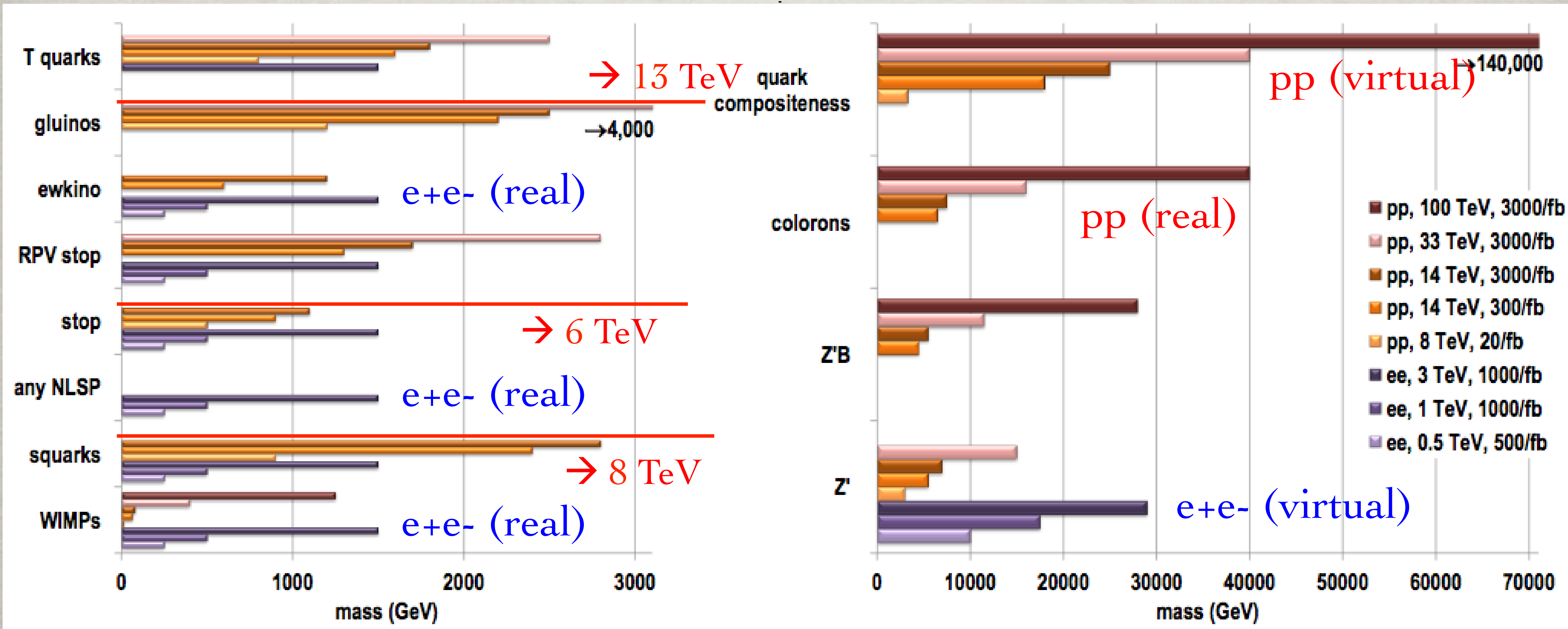
~ 6x over LHC

Colored Resonances:



New Particle Searches

Snowmass NP report, 1311.0299



e+e- & pp complementarity
for a broad range of searches.

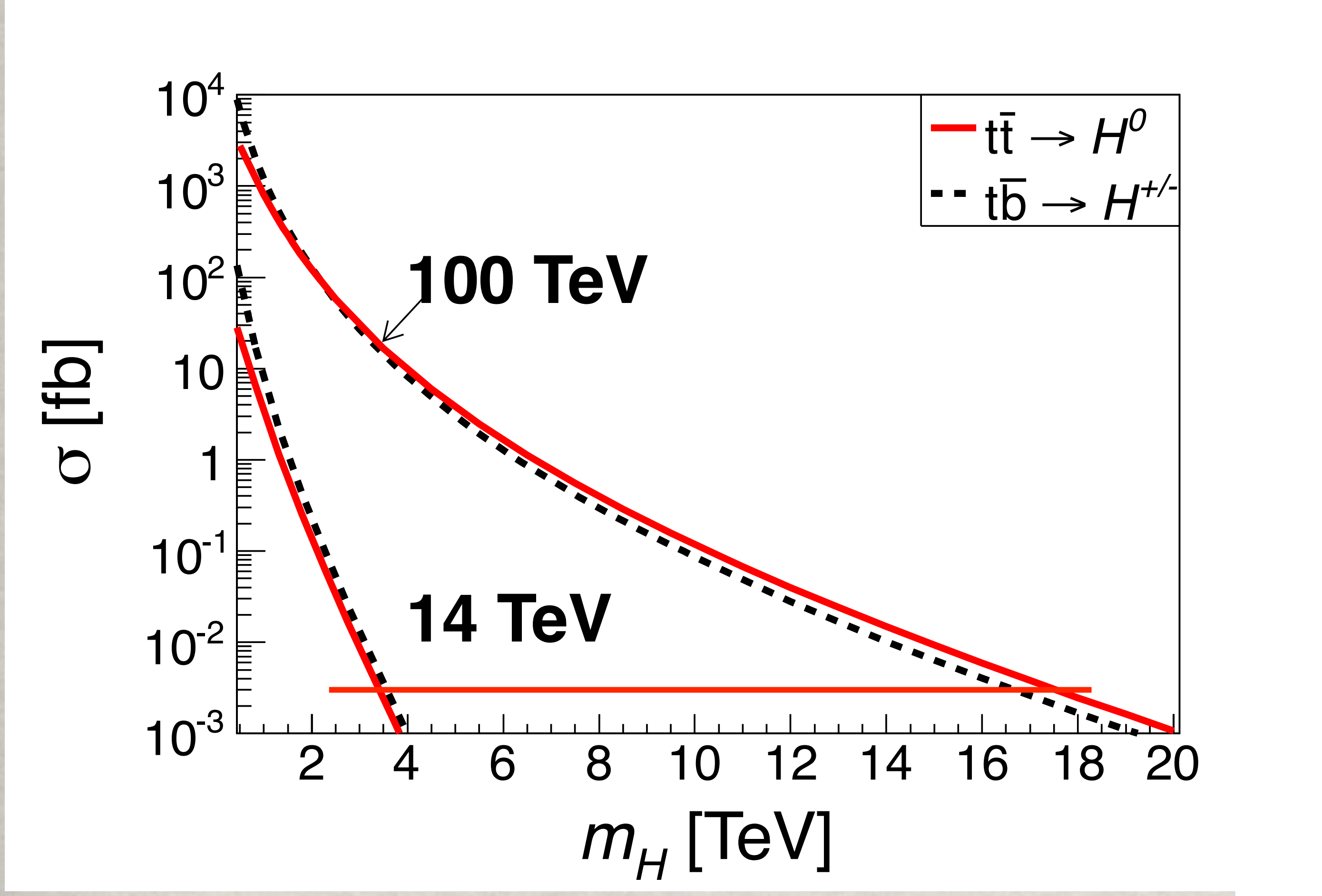
Other Rich Physics Opportunities

- Bread & butter SM physics:
  WW, tt threshold options at FCC_{ee}
  "top window" to new physics at FCC_{hh}
  EW vector boson showering at FCC_{hh}

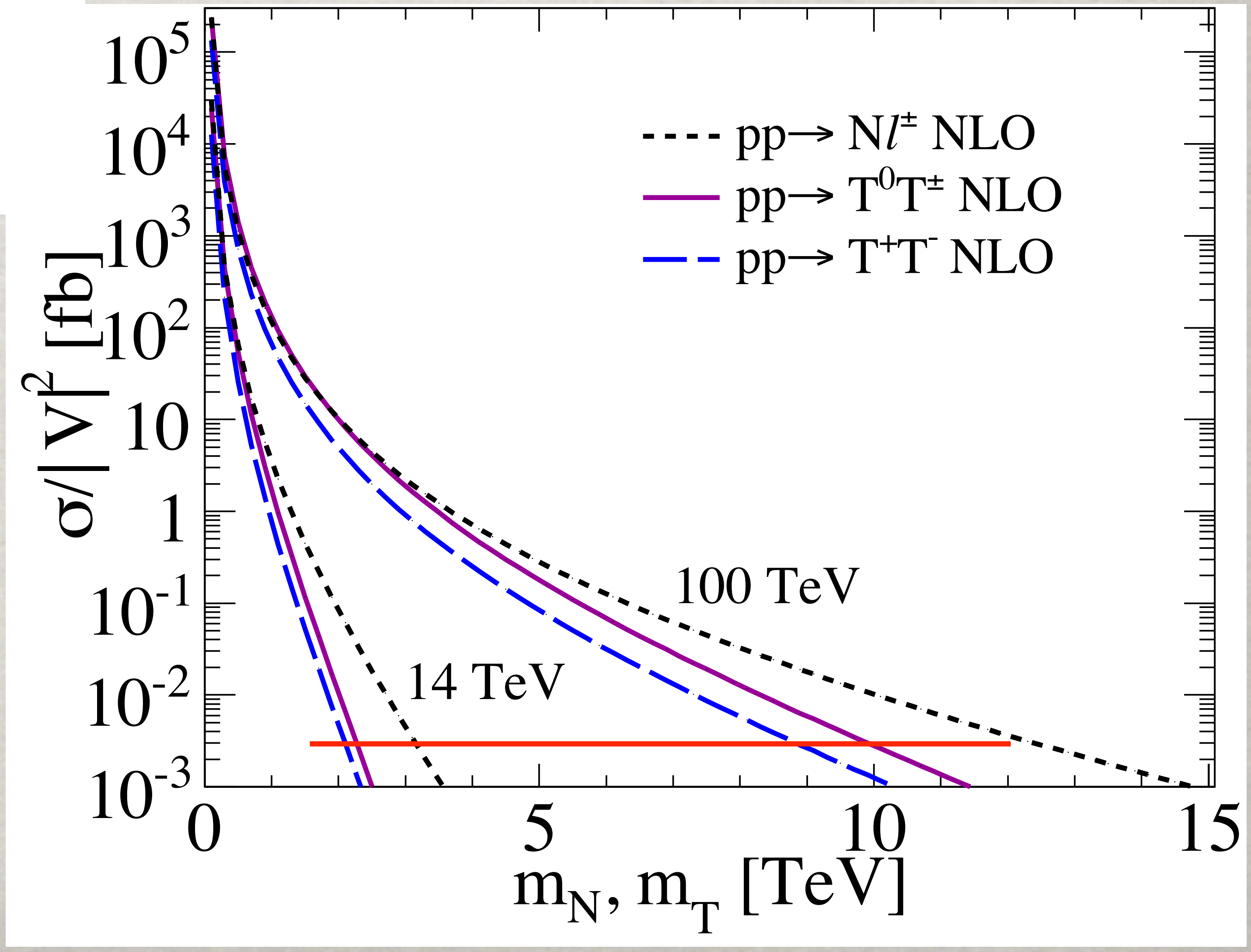
- $W_L W_L$ scattering at $E_{ww} > 10 – 20$ TeV

- Probe extended Higgs sector
  TeV scale seesaw for neutrino masses …

Heavy Higgs bosons: H^0, $H^\pm$



New (vector-like) leptons



Mass reach at 100 TeV:
~ 5x over LHC

Conclusions

- Higgs boson is a new class. New physics BSM → "under the Higgs lamppost"

- It calls for new colliders:
  Precision: FCC_{ee}/CEPC
  Tera Z: ΔM_Z, $\Delta\Gamma_Z < 0.1$ MeV, $\Delta\sin^2\theta_w < 10^{-6}$.
  At thresholds: $\Delta M_W \sim 1$ MeV, $\Delta m_t \sim 10$ MeV
  Mega Higgs: $\kappa_v \sim 0.2\%$, $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.
  Energy frontier: FCC_{hh}/SPPC
  $\lambda_{hhh} < 10\%$ → Conclusive for EWPT
  6x LHC reach: 10 – 30 TeV → fine-tune $< 10^{-4}$
  WIPM DM mass ~ 1 – 5 TeV

P5 Five Science Drivers

Report of the Particle Physics Project Prioritization Panel, May 2014

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles